INTEGRATING SAFETY AND BIM: AUTOMATED CONSTRUCTION HAZARD IDENTIFICATION AND PREVENTION

A Thesis
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in
School of Civil and Environmental Engineering

Civil and Environmental Engineering
Georgia Institute of Technology
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To my parents, Weizhen Cao and Jianmin Zhang.

ACKNOWLEDGEMENTS

First and foremost, I want to thank my advisor Professor Kimberly E. Kurtis and co-advisor Professor Charles M. Eastman for their guidance and support. It has been an honor to be their Ph.D. student. I appreciate all their contributions of time and idea to make my Ph.D. experience productive, simulating, and rewarding. I also want to thank my committee members Professor Lawrence F. Kahn, Professor Yong K. Cho, Professor John Haymaker, and also Dr. Frank Boukamp, and Dr. Jochen Teizer for their advice, time, comments, and help.

The members of the construction research group have contributed immensely to both my professional and personal time at Georgia Tech. The group has been a source of friendships, good advice, and collaboration. Especially, I am grateful for the fun group who stuck it out in grad school with me: Cheng Tao, Yihai Fang, Nipesh Pradhananga, Soumitry Jagadev Ray, Eric Marks, Kyungki Kim, Jun Wang, Aaron Costin, Manu Venugopal, and also Jin-kook Lee from College of Architecture. Special thanks go to Nipesh for helping me with the experimental setup and monitoring at construction sites from 5 am to 6 pm.

I gratefully acknowledge numerous companies that generously supported/sponsored my research including Skanska Finland, Skanska USA, McCarthy, Chevron ETC, Tekla, VTT Technical Research Centre of Finland, Autodesk and etc. Without the resources they provided, I would not have been able to test and implement my research idea.

Also, I would not be able to survive and stay sane in grad school without a good support system: friends. Feifei Qian, Zhongyu Yu, Min Zhu, Shun Zhang, Pengxuan Chen, Yuanyuan Lin, Mollie Baxley, Kirsten Jackson and many others made my time

enjoyable and have become a part of my life. Thank you all for your inexhaustible encouragement and the part you all played in helping me get to this point. I cannot tell you how lucky I am to have your friendship.

Lastly, I would like to thank my family for all their love and encouragement. My family is always my inspiration and they have been very supportive of me all these years. My parents encouraged me to dream big and had played the most remarkable role in my life. They always believe in me and supports me whatever decisions I make as a whole person and as a responsible being. My uncle Shaoxiong Wu and auntie Qiuping Shi took a great care of me and have been a great source of advice, which is so appreciated. And most of all, I feel extremely lucky to meet my loving, supportive, and patient fiancé Yunfei at Georgia Tech. Thank you for always being there for me. Thank you for your unconditional love. I could not ask for more.

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SUMMARY

Safety of workers in the construction environment remains one of the greatest challenges faced by the construction industry today. Activity-based hazard identification and prevention is an efficient method to minimize potential safety hazards during project front-end planning. However, its implementation is limited because construction safety information and knowledge tends to be scattered and fragmented throughout safety regulations, accident records, and experience. Additionally, hazards caused by the interaction between two activities are difficult to identify in the planning phase because construction sites are dynamic environments where workspace conflict of various work activities often results in workplace hazards. With the advancement of information technology in the building and construction industry, a missing link between effective activity-level construction planning and Building Information Modeling (BIM) becomes more evident.

The objectives of this study are 1) to formalize the safety management knowledge and to integrate safety aspects into BIM, and 2) to facilitate activity-based hazard identification and prevention in construction planning. The research scope is limited to concrete construction activities due to their high risk of hazards. To start with, a Construction Safety Ontology is created to organize, store, and re-use construction safety knowledge. Secondly, activity-based workspace visualization and congestion identification methods are investigated to study the hazards caused by the interaction between activities. Computational algorithms are created to process and retrieve activity-based workspace parameters through location tracking data of workers collected by remote sensing technology. Lastly, by introducing workspace parameters into ontology and connecting the ontology with BIM, automated workspace analysis

along with job hazard analysis are explored. Results indicate that potential safety hazards can be identified, recorded, analyzed, and prevented in BIM.

This study integrates aspects of construction safety into current BIM workflow, which enables performing hazard identification and prevention early in the project planning phase. The created ontology shows its potential to facilitate the integration of safety knowledge with construction processes and can be used as an extensible and shareable knowledge base for conducting various hazard analyses. In addition, developed safety analysis prototypes can serve as training material for daily safety orientation at jobsites to improve worker safety awareness by understanding the activity-specific safety issue and mitigation procedures.

CHAPTER I

INTRODUCTION

This chapter introduces the challenge in construction safety. The motivation of this thesis is explained, followed by a brief definition of the problem. At the end of this chapter, a brief outline of the thesis is also provided to help the readers understand the flow of the thesis.

1.1 Motivation

In the past two decades more than 26,000 U.S. construction workers have died at work. That equates to approximately five construction worker deaths every working day [100]. According to the safety statistics published by the Census of Fatal Occupational Injuries (CFOI) [19], construction industry has been leading the occupational fatality number among goods producing industries in the private industry division in the past two decades. Table 1 summarizes the occupational fatality statistics between 2005 and 2012 of construction industry by event or exposure type. As an average, a substantial fraction (35%) of the overall fatalities during this period was due to falls, followed by transportation (26%), contact with objects and equipment (18%), exposure to harmful substances (15%), and others (6%).

Table 1: Occupational fatalities by event or exposure, 2005-2012

Event or exposure	2005	2006	2007	2008	2009	2010	2011	2012
Fall, slips, trips	394	433	447	336	283	264	262	290
Contact with objects and equipment	244	216	206	201	151	138	122	136
Exposure to harmful substances	164	191	182	132	132	126	112	102
Transportation incidents	318	323	296	241	213	188	197	234
Others	72	76	73	65	55	58	45	44
Total fatalities	**1192**	**1239**	**1204**	**975**	**834**	**774**	**738**	**806**

Proactive job hazard analysis performed repeatedly prior to performance of any task is considered to be an effective and essential industrial safety measure. However, construction sites present significant obstacles to repeated job hazard analysis. Construction sites undergo dynamic change in ways that fixed industrial facilities do not: work teams are transient, the physical structure and spaces change constantly, and sites are exposed to the environment and changes in weather. Another difference is that in construction, workers of one team are frequently exposed to dangers posed by the workers of other, unrelated teams [90].

Planning for safety typically involves identification of all potential hazards, and the decision on choosing corresponding safety measures [10]. Precisely and accurately identifying the potential safety hazards is critical to the safety planning process. However, construction safety planning is generally independent of the project execution planning and involves different actors. This separation and the resulting lack of communication create difficulties for safety engineers to analyze *what, when, why, and where* safety measures are needed for preventing accidents. The industry is in need of improving the existing paper-based and manual safety processes (see Figure 1 and 2), which is labor-intensive, time-consuming, and thus highly inefficient.

Figure 1: Paper-based safety forms

The growing implementation of Building Information Modeling (BIM) in the AEC/FM industry is changing the way safety issues can be approached. According to 2014 SmartMarket Report [68], improved jobsite safety is considered as a

Figure 2: Different construction safety regulations from all contractors for a single project

highly important benefit to improve Return on Investment (ROI) of BIM. However, only 7% of constractors cited *Improved Safety* as one of top three BIM benefit for their organization (see Figure 3), and only 2% in US being the lowest when ranked by country. Also, only 6% contractors cite *Safety Planning/Training* as a top three activity that their company leverages BIM in pre-construction planning. Hence, the low rating should be interpreted as a lack of experience with improving jobsite safety leveraging BIM rather than a lack of interest. This research aims to take advantage of the potential that BIM offers for safety in construction design and planning. This facilitates the integration of construction safety practices in BIM by automatically detecting and mitigating hazards.

This research proposes a BIM-based safety hazard identification and prevention framework which intends to identify safety hazard early in the construction planning phase. Three types of hazards are discussed in this study:

1. Unsafe work conditions. Workers are exposed to potential hazardous zone/space. Fall hazards are chosen as the focus since it is one of the greatest hazards on construction sites.

2. Activity-based hazards. These hazards are specifically associated with workers'

activity. For example, fall hazard and pinch finger hazard are associated with adjusting rebar for columns.

3. Hazards caused by activity interaction. These hazards are related to the space conflict by two activities. Struck-by falling objects hazards are selected since it is the leading cause for crane-related fatalities [29].

The three types of hazards deal with three different hazard levels with increasing complexity. And three safety analysis prototype applications are developed to detect and prevent each hazard in respective.

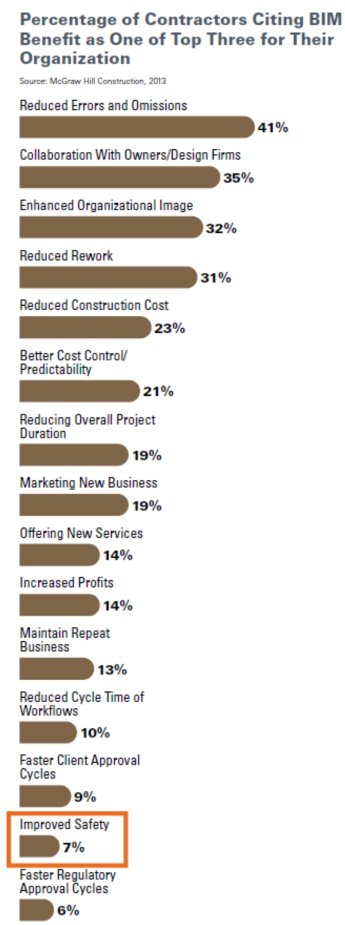


Figure 3: Percentage of contractors citing BIM benefit as one of top three for their organization [68]

1.2 Organization of the Thesis

Chapter 1 introduces the challenge in construction safety, explains the motivation of this thesis, followed by a brief definition of the problem.

Chapter 2 describes the research methodology for automated construction hazard identification and prevention leveraging BIM. The research objectives, scope, and research hypothesis are stated, along with the research framework showing different phases of the research, including data collection, processing, and safety analysis.

Chapter 3 explains the need for better construction safety management in the construction industry, then describes the development and evaluation of the proposed Construction Safety Ontology.

Chapter 4 focuses on the first type of hazard: unsafe condition (fall hazard). It presents an automated rule-based checking system for BIM and how safety planning can be integrated in work breakdown structures and project schedules. Safety rule interpretation and rule-based algorithms for fall protection are presented, along with a case study to demonstrate its usefulness.

Chapter 5 deals with second type of hazard: activity-based hazards. It shows an automated Job Hazard Analysis framework to enable early hazard identification and BIM-based visualization. Detailed descriptions of how individuals are generated based on both ontology and BIM, and how associated safety knowledge can be inferred by defining rules of logic are presented.

Chapter 6 handles the third type of hazard: hazards caused by activity interaction. It describes an approach that collect, formalize and reuse historical activity-specific workspace information for automated activity-based workspace visualization and workspace congestion identification in BIM. It explains the process of data collection, workspace parameter computation, and its integration into Construction Safety Ontology.

Chapter 7 explains the integration of construction safety design, planning, and operation with project workflow. Use cases applying automated hazard identification and prevention are defined. Also, a review and comparsion on BIM platforms for supporting construction safety planning is discussed.

Chapter 8 summarizes the findings and concludes the thesis. Also discussed are the limitations and future extension of this research.

CHAPTER II

RESEARCH HYPOTHESIS AND METHODOLOGY

This chapter explains the research methodology and framework for automated construction hazard identification and prevention leveraging BIM. The first several sections state the research objectives, scope, and research hypothesis. The subsequent sections describe the different phases of the research, including data collection, data processing, and safety analysis.

2.1 Research Objectives

The objectives of the research are listed below,

1. To formalize the safety management knowledge and to integrate safety aspects with BIM;
2. To facilitate hazards identification and prevention in construction planning phase;
3. To create a general approach to collect, formalize, and reuse historical activity-specific workspace information for visualization and hazards identification.

2.2 Scope

- The proposed study focuses on concrete construction activities due to their high risk of hazards and severity of incidents and injuries.
- In terms of technology for data collection, Global Positioning System (GPS) are used for worker location tracking. GPS is well known to work independently (defined as a device that may not require any other installation of technology

on a project site, other than a device on the resource to track it) and provide real-time data (defined as equal or greater than 1 Hz data update rate). GPS devices are also affordable and easy to install.

- It is assumed that the information provided by BIM and schedule is correct and updated.

2.3 Research Hypothesis

The following hypotheses are tested by implementing the research methodology described in the next chapter,

- Construction safety knowledge can be formalized and can be connected with BIM by developing a construction safety ontology.
- The integration of construction safety ontology and BIM enables potential hazard identification and prevention
- Workspace parameters can be retrieved from collected location tracking data and be used for generating new workspace in BIM

Three important research questions were put forth during the development effort of this research that formed the basis for initiating this research and are central to answering this hypothesis. These are as follows:

1. How can construction safety knowledge be formalized using engineering ontology in a consistent, testable, and reusable way?
2. How to integrate construction safety ontology with existing building product and process model to facilitate hazards identification and prevention?
3. How to develop a method for construction workspace modeling, visualization, and analysis?

2.4 Problem Description

Review of existing studies revealed the lack of research in following areas:

1. Activity-based hazard identification and prevention is an efficient method to eliminate potential safety hazards in project front-end planning. However, it cannot be achieved as current construction safety information and knowledge carried by safety regulations, accident records, and safety engineer's experience are scattered and fragmented. With the advancement of information technology in the building and construction industry, a missing link between effective activity-level construction planning and BIM becomes more evident.

2. A construction site is a dynamic environment in which workspaces of construction activities continuously change in aspects of space and time throughout the entire lifecycle of a project. The locations and volumes of these spaces change in three dimensions and across time, according to project-specific design. Hence, congestion of different work activities cannot be eliminated, which often leads to safety hazards. Currently, an activity-level construction planning approach is needed to identify safety hazard lead by the interaction between activities.

2.5 Overview of Framework

The research framework is illustrated in Figure 4 showing what data and knowledge are needed, how they are processed, complied, and finally developed into safety analysis level.

The first phase of the research consists of:

1. Understanding Occupational Safety and Health Administration (OSHA) regulation and collecting safety management best practices;

2. Analysis and understanding of how BIM schema and scheduling can be leveraged to support construction safety management;

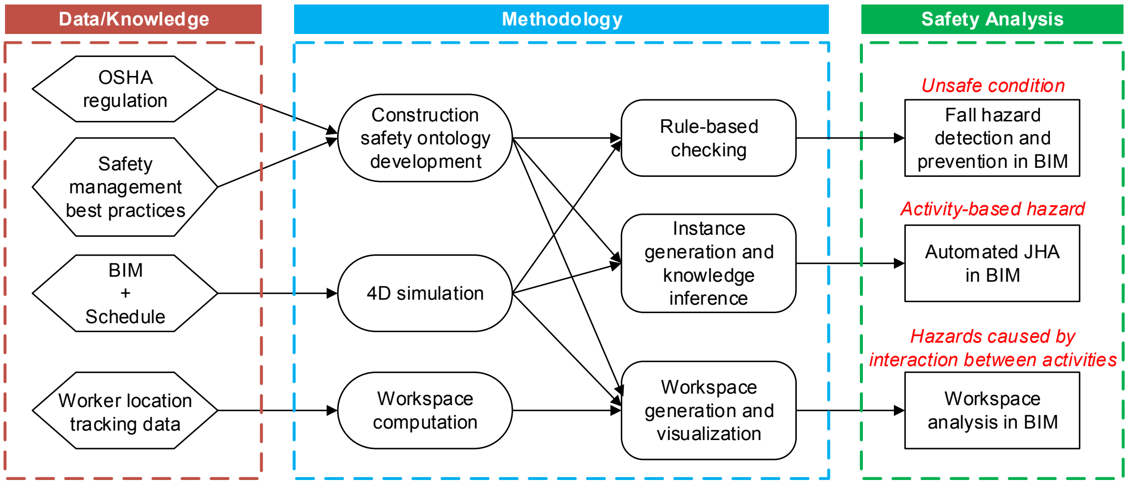


Figure 4: Framework of research methodology.

3. Conducting experiments to collect location tracking data of construction crew.

In the second phase, data and knowledge are processed and compiled in a formal way:

1. Based on safety regulations and best safety practices, an ontology-based definition for construction safety management is created. By mapping developed construction safety rules with 4D simulation of the project, potential unsafe working condition (fall hazards) can be detected dynamically according to the project schedule based on predefined rules.

2. Instances/individuals are generated based on both the ontology and BIM. Associated safety knowledge can also be inferred by defining rules of logic. Then, activity-based hazards can be detected and prevention methods can be found accordingly. This step also involves the preparation of a knowledge base and setting up the modeling criteria.

3. Based on geometry and schedule information from BIM and location tracking data from construction site, a set of activity-based workspace parameters

are computed. These parameters can then be used to represent and visualize activity-based workspace in BIM.

In the last phase, three BIM-based safety analysis prototypes were developed to further validate the research methodology at application level. These three applications consist of:

1. Fall hazard detection and prevention in BIM:

   More than 30% of the construction fatal injuries are related to fall from height. A rule-based prototype application was developed to detect potential fall hazard and to install corresponding protective system for Building information Models. OSHA safety regulation is used in the prototype, but it also supports customization of the rules based on best practices from different organizations. The prototype has been used to address edge of slab, holes in slab, openings in walls, and it also consider the pour break of slabs. Safety protective system such as guardrail system and cover are created automatically in BIM. Also, the project schedule will be updated to include the installation and removal of the safety protective system so that safety is no longer an afterthought. As a result, the developed automated safety checking system informs construction engineers and managers by reporting, why, where, when, and what safety measures are needed for preventing fall-related accidents before construction starts.

2. Automated job hazard analysis (JHA) in BIM: JHA is a technique that focuses on job tasks as a way to identify hazards before they occur. JHA is generally time-consuming, labor-intensive, and hard to keep up-to-date with changing construction schedules. To address these issues, an automated JHA application was developed to facilitate the JHA process. It was done by integrating JHA databases with Building Information Models. The prototype introduces

significant automation in existing manual/experience-based JHA processes, allowing a user to apply different sets of JHA on building information models. Simulation of safety and visualization of models with safety resources becomes possible. JHA report along with 4D simulation of the BIM can be generated automatically from the system, then to be used by safety and field staff on construction sites as safety guidance. It has the potential to enhance the JHA process by reducing time commitment and improving safety awareness.

3. Workspace analysis in BIM:

   Construction industry has high accident and fatality rates due to congested conditions on construction sites. In order to enable effective activity-level construction planning to avoid workspace congestion, a new construction planning tool was prototyped. Workspace parameters are generated from empirical worker location tracking data and then visualized in BIM. Then these spaces are used to detect congested work area and also potential safety hazards. The application has been tested for cast-in-place concrete construction activities such as column and slab construction. The developed application can support project stakeholders, such as engineers, planners, construction managers, and site workers with identification and visualization of congested workspaces. Hence, it assists to create safer site layout and project schedule.

Thesis Statement: The hazard identification and prevention in construction planning can be significantly facilitated by the integration of BIM and construction safety knowledge.

CHAPTER III

ONTOLOGY-BASED SEMANTIC MODELING OF CONSTRUCTION SAFETY KNOWLEDGE

This chapter first explains the need for better construction safety management in the construction industry, then describes the development and evaluation of the proposed Construction Safety Ontology.

3.1 Introduction

Construction safety related knowledge and project specific information are scattered and fragmented. Despite technological advancements of information and knowledge management in the building and construction industry, a link between safety management and information models is still missing. The objective of this research is to investigate a new approach to organize, store and re-use construction safety knowledge. A construction safety ontology is proposed to formalize the safety management knowledge. It consists of three main domain ontology models, Construction Product Model, Construction Process Model, and Construction Safety Model.

3.2 Background

3.2.1 Current construction safety planning and knowledge management practice

The complex and dynamic nature of the construction industry and its on-site work patterns are widely recognized. This separates it from the manufacturing industry, which has mostly stationary fabrication settings. Safety planning in an unstructured construction environment is thus more challenging. The most severe consequence from bad safety planning and execution is loss of life. Significant time and economic resources are lost when workers are injured on the jobsite. Some practitioners even claim that construction sites are often under-resourced and under-planned when it comes to safety planning [37]. The mandate of the construction industry is to provide a safe and healthy work environment. The existing safety management culture in a construction company focuses on checking regulations from the Occupational Safety and Health Administration (OSHA). Often companies apply more stringent best practices in safety and health that go beyond providing education, training, and personal protective equipment (PPE) to workers [2]. The current state of safety planning in construction can be summarized:

- Traditional safety planning relies on frequent manual observations, is labor-intensive, time-consuming, and thus highly inefficient. Safety planning together with project execution planning can convey what is to be built, what safety measures are necessary when, where and why [20]. The link between planning for safety and work task execution is often weak: for example, many contractors use two-dimensional drawings (2D) or field observations to determine hazard prevention techniques. Since their approach is manual and based on experience, the observed results are often error-prone due to subjective judgments of the decision maker.

- Safety knowledge is difficult to transfer by safety regulations alone. Existing safety rules, regulations, and best practices have demonstrated impact. A trend towards zero accidents can be shown in indices such as the Total Recordable Incident Rate (TRIR) published by the Construction Industry Institute [26]. Even though safety records have improved compared to ten years ago, improvement in recent years has slowed down, or in the last few years began again to get worse. One main contributor for the recent increase in incidents is knowledge transfer of safety best practices. As companies hire new personnel it becomes difficult for them to adapt to a new safety culture. Though many job sites require safety orientation and training, it is demanding for workers to acquire the knowledge in a short time and stick to the rules accordingly when performing design, planning, and work tasks.

- Construction site safety often remains the sole responsibility of the contractor. Design choices often determine construction methods and schedule; while limited attention is given to safety during the design phase [51]. Often designers do not fully understand the impact their work has on construction methods, schedule, and most importantly on safety. To date, the cooperation and communication among project stakeholders (owners, contractors, subcontractors, etc.) in regards to safety is quite limited at the front-end [11].

All of these are barriers creating hazards at the project planning and execution stages. The following section summarizes some of the research conducted to improve safety planning approaches based on historical data.

3.2.2 Ontology-based knowledge modeling in AEC industry

Gruber [44] defined ontology as "an explicit and formal specification of a conceptualization." Ideally, an ontology should (1) capture a shared understanding of a domain of interest and (2) provide a formal and machine manipulable model of the domain [57]. Ontologies are now central to many applications such as scientific knowledge portals, information management and integration systems, electronic commerce and web services. Ontologies have also been used in artificial intelligence to try to capture knowledge, and create a model of the knowledge base. There exist numerous examples of general and specific ontologies, such as medical, transportation, plant ontologies and others [8]. In recent years, ontologies have been adopted in many business and scientific communities as a way to share, reuse and process domain knowledge. The main areas, in which ontological modeling is applied, include communication and knowledge sharing, logic inference and reasoning, and knowledge reuse. Development of domain ontology in the construction industry has been another crucial step to improve knowledge management and workflow. Venugopal et al. [107] presented a formal classification structure for IFC implementations for the domain of Precast Concrete Industry to improve the interoperability of BIM applications. Lima et al. [63] implemented the e-COGNOS platform and have proven the benefit of semantic systems as they provided adequate search and indexing capabilities. This allowed for a systematic procedure for formally documenting and updating organizational knowledge and enhanced the customization functions in a knowledge management systems. The e-COGNOS platform presented the first comprehensive ontology-based portal for knowledge management in the construction domain. Akinci et al. [7] envisioned semantic CAD/GIS web services can provide a way to address the lack of interoperability between CAD and GIS platform. El-Diraby and Osman [38] developed a domain ontology for construction concepts in urban infrastructure products. Wang and Boukamp [110] presented a framework aiming to improve access to a company's JHA knowledge by using ontologies for structuring knowledge about activities, job steps, and hazards. Zhang et al. [114] proposed a framework for automated, ontology-based job hazard analysis in building information models. An ontology-based semantic modeling approach of regulation constraints based on proposed CQIEontology and construction process ontology was explored by Zhong et al. [117] aiming to integrate regulation knowledge with the definition and execution of construction processes. This led to the conclusion that the proposed regulation-based automated construction quality compliance checking as a parallel activity to construction planning and execution can improve efficiency, reduce errors, and save human resources. Undoubtedly, these current research efforts have paved the way towards an automated compliance checking and knowledge modeling in construction industry.

However, from the literature review given above, it can be concluded that most of the existing efforts have focused on a domain ontology for construction concepts and model exchange. An ontology to represent construction safety knowledge in a comprehensive way is lacking. In terms of knowledge preparation, Natural Language Processing (NLP) techniques have been leveraged to extract information from regulation text. Zhang and El-Gohary [112] explored the effectiveness of utilizing syntactic and semantic features of the text to automatically extract regulatory information from building codes using automated Information Extraction (IE) approach. Chi et al. [24] presented an approach based on text classification to support the automation of JHA. Kim et al. [58] proposed an automated information retrieval system that can search for and provide similar accident cases. The retrieval system extracts building information modeling objects and composes a query set by combining BIM objects with a project management information system. However, knowledge extraction and preparation using NLP is beyond the scope of this study. Also, NLP may have limited application in construction safety, since safety rules are limited in number, rarely change, and often require decades to update.

3.3 Objective and Scope

The objective of this Chapter is to design a construction safety ontology to formalize the safety management knowledge and to integrate safety aspects with BIM. The development of the ontology does not consider the use of NLP methods. Also, while the possibility to connect the ontology to BIM is explored (in Chapter 5 and 6), the actual semantic modeling of building information using, for example Industry Foundation Classes (IFCs), is not investigated in this study. Considering that there is no "perfect" ontology and no "optimum" classification or concept hierarchy [96], it is important to note that the proposed Construction Safety Ontology is not intended to cover a domain of interest in full detail. Rather, as a domain ontology, it intends to capture the most fundamental concepts in the domain in a structured and extendable format [39].

3.4 Research Methodology

The reasons for using ontologies for safety knowledge modeling are as follows. First, they can be shared and used to link information from different knowledge domains together. Second, ontologies support consistency checking and reasoning. In addition, concepts used in regulations and their semantic relationships can be represented in the form of classes and properties of the ontology in an intuitive way [117].

Automated reasoning about specifications requires the specifications to be modeled in a computer-interpretable way [15]. In order to make construction safety specification checking an easier and more efficient process for safety managers or superintendents, an ontology-based semantic modeling of safety specifications is explored. The detailed research tasks (Figure 5) are as follows:

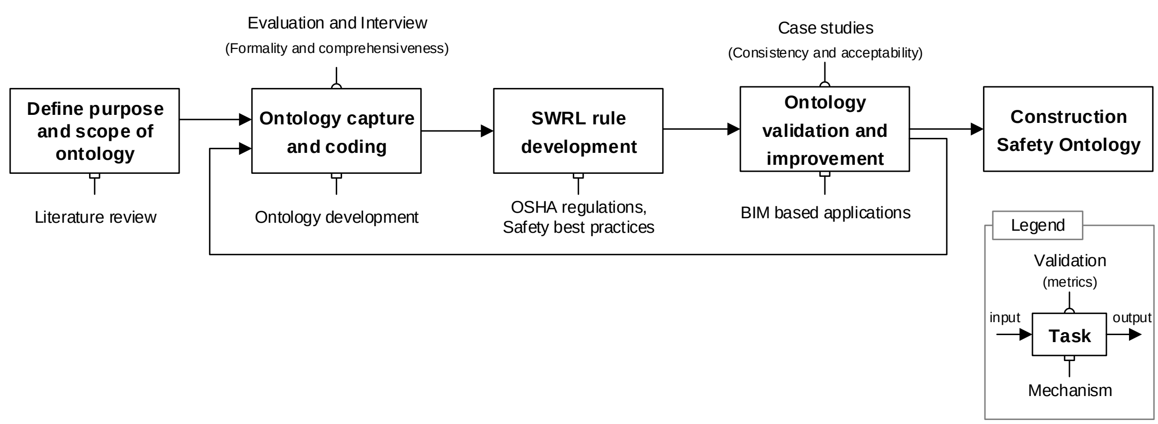


Figure 5: Research tasks in construction safety ontology development.

3.4.1 Define the purpose and the scope of the safety ontology

The purpose of developing a construction safety ontology is not only to formalize the current knowledge, but also to support safety hazard identification and mitigation through BIM. The development of the ontology should support the integration of the knowledge with building information models. Existing BIM schema, such as the IFCs, are considered.

3.4.2 Ontology capturing and coding

The knowledge sources considered for identifying relevant concepts and coding the safety ontology include the OSHA regulation 1926 [76], the Occupational Injury and Illness Classification Manual [18], and Construction Solutions Database [28]. These include construction safety regulations and industry safety best practice reports. In order to design and maintain a meaningful, correct, and minimally redundant ontology, the consistency of the ontology is checked and verified using an automated reasoner. A Description Logic (DL) reasoner is able to perform various automated inferencing services on the developed OWL-based ontology, such as determining whether or not the ontology includes inconsistent classes. Automated consistency checking is crucial as manual checking would be highly time-intensive. It helps in assessing the overall consistency of the ontology. In addition, interviews with domain experts were conducted to further evaluate the ontology content.

3.4.3 Semantic Web Rule Language (SWRL) rule development

The Semantic Web Rule Language is the preferred language for the Semantic Web that can be used to express rules as well as logic, combining OWL DL or OWL Lite with a subset of the Rule Markup Language [53]. Selected OSHA regulations and industry safety best practices are coded in SWRL rule formats, compatible with ontology classes and relationship. This enables automated reasoning to test the applicability of safety rules and regulations for different projects. An additional objective was to have rules that can be configured and adjusted by a user. As the rules will likely be applied to some projects with unique circumstances, user-friendliness to reflect advantages of competing construction methods and other accepted best safety practices as well as human involvement are key concerns in the traditionally risk-averse construction industry.

3.4.4 Ontology validation and improvement

Three BIM-based applications (see Chapter 4, 5, 6) are developed to automatically identify work activity related safety hazards, suggest mitigation methods, and visualize relevant safety information, such as hazard zones. All of them support safety management in advancing decision making at the front-end, before work tasks start. The feedback from the application then goes back to ontology development to make further improvement. Construction Safety Ontology then becomes the final output.

3.5 Taxonomical Structure of the Construction Safety Ontology

The goal and intention of this research is to formalize construction safety planning knowledge by developing a construction safety ontology. As shown in Figure 6, the construction safety ontology consists of three main domain ontology models including: *Construction Product Model*, *Construction Process Model*, and *Construction Safety Model*.

The *Construction Product Model* contains building element information such as column, slab, and wall information, and provides the main interface for connecting the ontology and a BIM platform. It follows the structure of the IFC schema and mainly includes subtypes of IfcBuildingElement. This building element includes major functional parts of a building; examples are foundation, floor, roof, wall [1].

The *Construction Process Model* includes the construction plan of the project along with construction resources, such as equipment, material and labor. The model used in this study was based on several existing studies on construction process modeling. Specifically, it addressed Benevolenskiy et al. [12] and Wang and Boukamp [110] and modified it to fit to the construction safety purpose. *Task*, *Activity*, and

Job_Step represent the hierarchical breakdown of the construction process. *Task* is related to Building Component through the "produce" property. For instance, in cast-in-place (CIP) construction, *Task_CIP_Column* produces *CIP_Column*. Each of the tasks consists of a set of activities, and then each activity consists of different job steps. The construction method is associated with the activity and construction resources are connected with each job step.

The *Construction Safety Model* contains construction safety related knowledge, such as potential hazard, specification from regulations, mitigation recommendation, and safety resource. Each *Job_Step* is associated with multiple *Potential_Hazard* instances through the "hasHazards" property. Then, each *Potential_Hazard* is controlled by some *Mitigation_Recommendation* to eliminate or reduce the safety risk. Some of the *Mitigation_Recommendation* requires additional Resource instances such as safety protective systems or equipment. These resources are regulated by *Safety_Specification* instances derived from safety regulation or best safety practices.

The Resource class hierarchy is further explained in Figure7 following the same legend in Figure 6. It contains four subclasses including *Equipment*, *Material*, *Labor* and *Safety_Measure*. The *Safety_Measure* has five subclasses: 1) *Training* to train workers to conduct the job in a safe manner, 2)*Inspection*, if the job step needs to be inspected by safety personnel, 3) *Safe_guard*, for example, guardrail systems which are applied on instances of *Building_Element*, 4) *Protective_Space*, for instance, signs and barriers shall be erected to limit the access to the post-tensioning area to only authorized personnel during tensioning operations [77], and 5)*Personal_Protective_Equipment*, such as gloves and lifelines.

The resulting construction safety ontology integrates safety planning and construction execution planning by linking safety knowledge to construction processes and products.

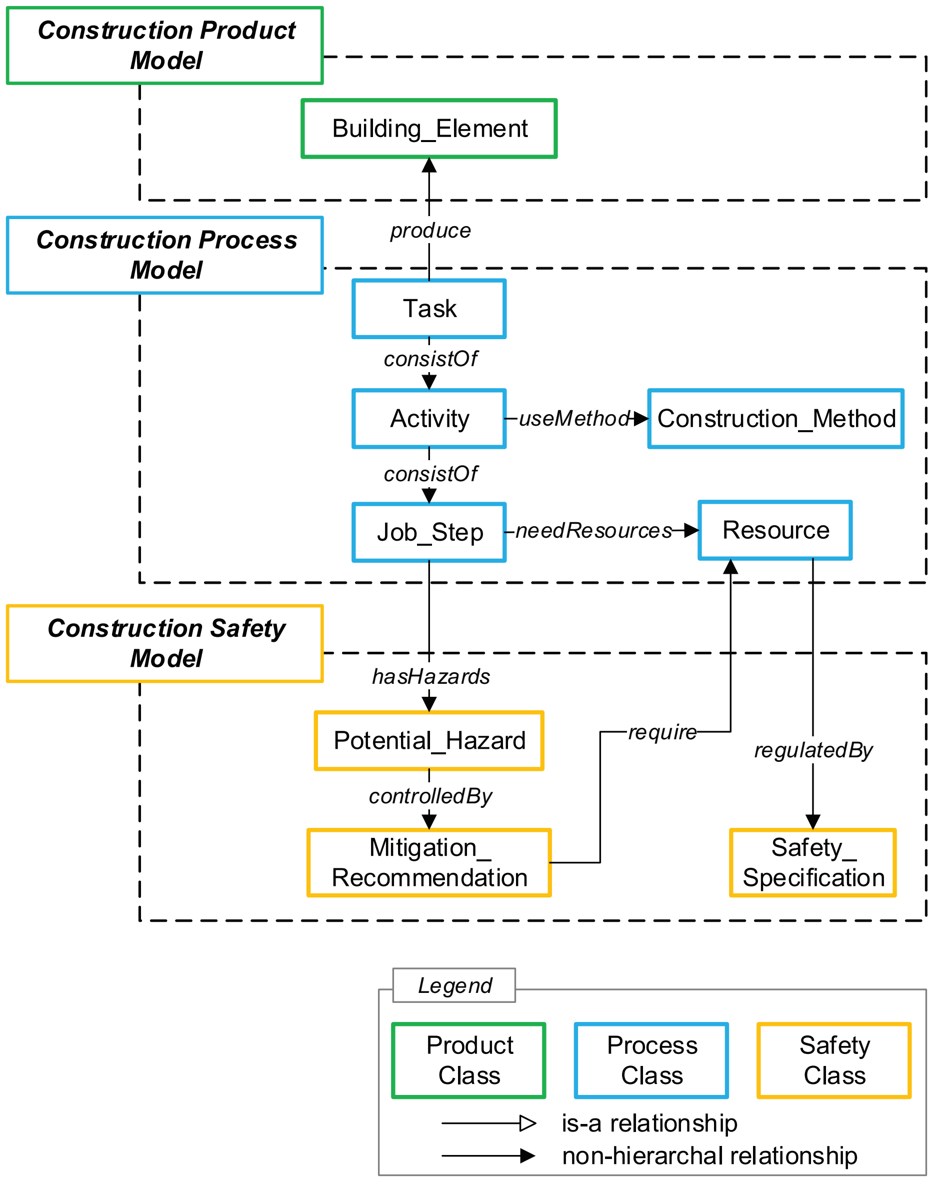


Figure 6: The Construction Safety Ontology

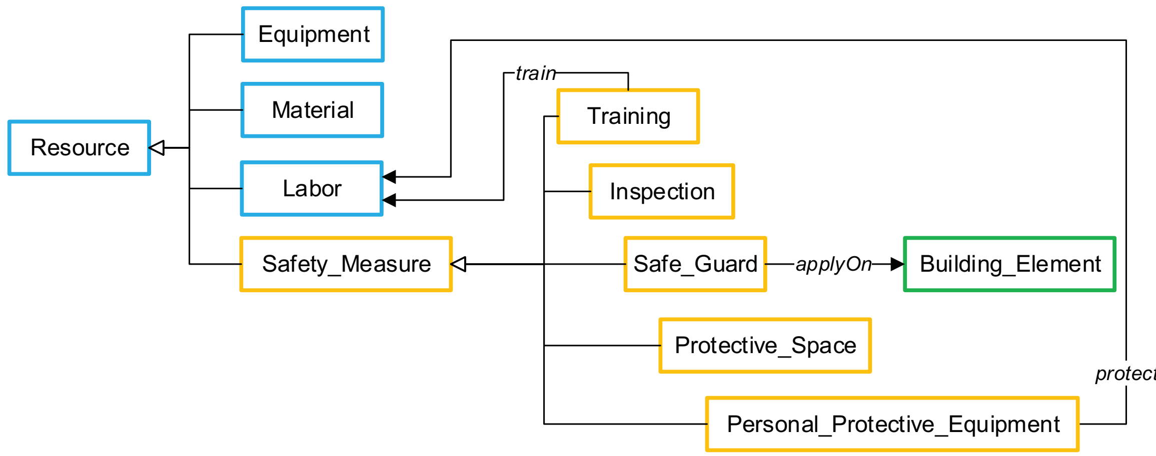


Figure 7: Resource class in the Construction Safety Ontology

Some of the terms used in construction industry are often used interchangeably, for example, "task" and "activity" can both refer to specific, defined items of work in construction plans. Given that, definitions of the main concepts used in the ontology are explained as following:

- *Task*: Task represents the necessary framework to permit scheduling of construction activities, along with estimating the resources required by the individual work tasks, and any necessary precedences or required sequence among the tasks. The task is corresponding to the lowest level in construction work breakdown structure of project schedule. Task can also produce a deliverable which is measurable. Some examples of task are wall, column, slab and etc.

- *Activity*: Formally, an activity is any subdivision of project tasks. While *Task* focuses on outcome, *Activity* focuses on actions. Hence, activity does not directly produce a building element. The duration of an *Activity* usually is no longer than a day. For example, place rebar cage, frame column and etc.

- *Job_Step*: Activity can be further decomposed into job steps. It is usually the smallest step for conducting job hazard analysis. It involves exactly one crew or one personnel. Table 2 summarizes the differences between *Task*, *Activity*, and *Job_Step*. Also, Figure 8 shows an example of column construction.

- *Construction_Method*: The procedures and techniques utilized during construction. Construction operations are generally classified according to specialized fields. Different construction methods will yield different job steps from activity.

- *Hazard*: A hazard is the potential for harm. A hazard often is associated with a condition or job step that, if left uncontrolled, can result in an injury or illness.

- *Mitigation_Recommendation*: Mitigation recommendation aims to control potential hazard before it occurs. Since different scenario may create same type of hazard but the mitigation recommendations are different depending on situation, *Mitigation_Recommendation* is associated with not only *Hazard* class, but also with *Task*, *Activity* and *Job_Step*.

- *Safety_Specification*: Safety specification refers to safety regulation or codes from OSHA and etc. It also includes safety best practices from different organizations.

Table 2: Property differences between Task, Activity, and Job_Step

Concepts \ Properties	Produce *Building_Element*?	NeedResources *Crew*?	Example
Task	Yes, min 1	Yes, min 1	*CIP_Column*
Activity	no	Yes, min 1	*Frame_Columns*
Job_Step	no	Yes, exactly 1	*Stand_Forms_Into_Place*

Three types of relationships are considered in the semantic modeling process of the Construction Safety Ontology: generalization, aggregation, and association.

- Generalization is the means by which differences among similar objects are ignored to form a higher order type in which the similarities can be emphasized

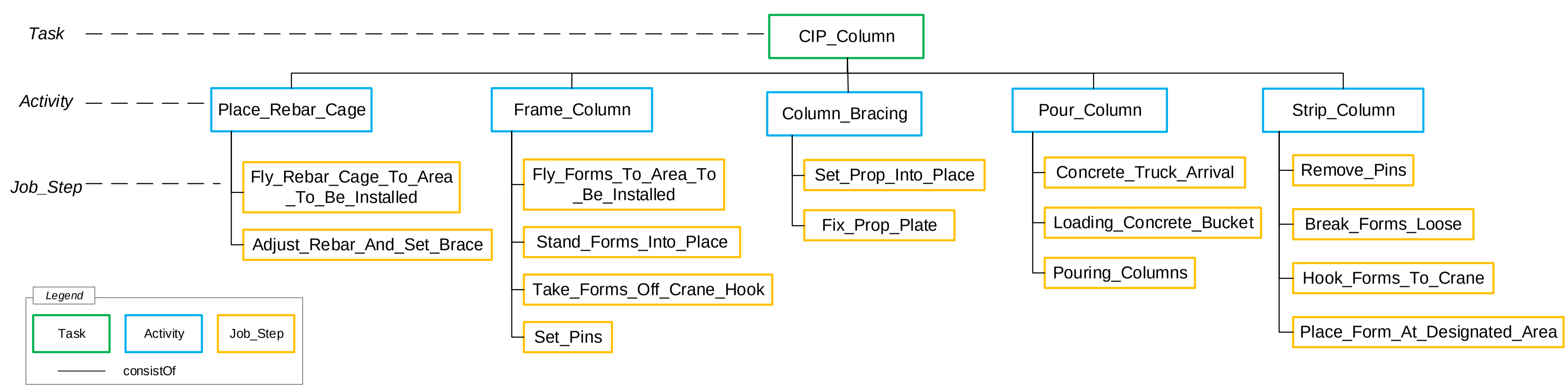


Figure 8: CIP column construction

[82]. It is realized in the ontology based on the hierarchical *is-a relationship* [74] as shown in Figure 6 and 7.

- Aggregation is the means by which relationships between low-level types can be considered a higher level type [108]. It is treated as *has-a* or *part-of* relationship.

- Association is a form of abstraction in which a relationship between member objects is considered a higher level set object [17]. The following OWL snippet (See Figure 9) shows an example of *consistOf* relationship between *Place_Rebar_Cage* and its *Job_Steps*.

```
<owl:Class rdf:about="#Place_Rebar_Cage">
 <rdfs:subClassOf>
  <owl:Restriction>
   <owl:onProperty>
    <owl:ObjectProperty rdf:about="#consistOf"/>
   </owl:onProperty>
   <owl:allValuesFrom>
    <owl:Class>
     <owl:intersectionOf rdf:parseType="Collection">
      <owl:Class rdf:about="#Fly_Rebar_Cage_To_Area_To_Be_Installed"/>
      <owl:Class rdf:about="#Adjust_Rebar_And_Set_Brace"/>
     </owl:intersectionOf>
    </owl:Class>
   </owl:allValuesFrom>
  </owl:Restriction>
 </rdfs:subClassOf>
</owl:Class>
```

Figure 9: OWL snippet shows an example of consistOf relationship between Place_Rebar_Cage and its Job_Steps.

3.6 Construction Safety Ontology Evaluation

Generally, ontology evaluation is roughly classified into two kinds: *form-based* (syntax) evaluation and *content-based* (semantic) evaluation. The developed ontology has been checked to ensure its consistency using the Pellet reasoner. Such a form-based evaluation as to whether the ontology being constructed is written properly in terms of its form/syntax is required to enable automatic reasoning. However, *content-based* evaluation is needed to evaluate whether the ontology properly represents the target, which can further assure the quality of ontology [16]. Two types of *content-based* evaluation methods were considered in this study: *agreement-based* and *task-based*. Content evaluation is first conducted through interviews with subject experts (*agreement-based*) and then further evaluated through developed applications (*task-based* evaluation), which will be discussed in Chapter 4, 5, and 6.

3.6.1 Automated consistency checking

The Construction Safety Ontology is automatically checked for syntax consistency using a DL reasoner: Pellet. A DL reasoner is able to perform various automated inferencing services, such as determining whether or not the ontology includes inconsistent classes. Automated consistency checking is crucial as manual checking would be highly time-intensive. It helps in assessing the overall consistency of the ontology. Pellet provides the service to check the consistency of an OWL ontology and a set of data descriptions, and also find implicit subclass relationships induced by the declaration in the ontology.

3.6.2 Construction safety expert evaluation interviews

Agreement evaluation is measured through the proportion of agreement that experts have with respect to ontology elements and structure. Task-based evaluation assesses what has to be supported by an ontology [42]. It measures an ontology according to its fitness to goals, preconditions, post conditions, constraints and options. The developed ontology is evaluated through interviews with subject experts and then tested through the developed safety analysis applications as a task-based evaluation, which will be discussed in the next three Chapters. One-on-one interviews were conducted with construction safety experts to evaluate the content and structure of the ontology. 10 professionals completed the survey whose time in the industry accumulates to about 115 years of practical work experience (see Table 3). The evaluation process consists of three major sections: 1) the taxonomy, relations, and axioms of construction safety ontology were first presented to safety professional, then 2) open discussion was held to explain the details of the ontology and also to receive constructive feedback, and 3) the participant was requested to evaluate the ontology through an online survey after the interview.

Table 3: Industry safety professional participants

Participant	Years of experience	Job title
1	20	Safety Engineering Supervisor
2	9	OSHA Inspector and Industrial Hygienist
3	35	Construction Project Manager
4	15	Safety Professional
5	10	Safety Director
6	5	Assistant Superintendent
7	5	Safety Engineer
8	1	Project Safety Coordinator
9	9	HSE Manager
10	6	Projects HSE Consultant

The survey used a Likert six-point scale to record the responses of experts, with 1 being the most favorable (see Table 4). The results indicate that:

- Participants find the concepts used to be in the range of "very familiar" to "familiar."
- Participants find the concepts and relations used to be "representative."
- Participants find the navigation through the ontology to be "easy".

- Participants "agree" that the ontology covers the main concepts and relations within the construction safety domain.

Table 4: Survey results

Question	Mean	Median	SD	Result
Are you familiar with the concepts used in the ontology?	1.50	1.5	0.5	"very familiar" to "familiar"
Do you think the concepts and relations used in the ontology is representative?	1.70	2	0.46	"representative"
How easy was it to understand and navigate through the ontology?	1.80	2	0.6	"easy"
Does the ontology cover the main concepts and relations within the Construction Safety domain?	1.90	2	0.54	"agree"

3.7 Discussions and Conclusions

3.7.1 Discussion and limitations

This chapter presents an ontology-based semantic modeling of construction safety knowledge framework. Construction Safety Ontology was developed to formalize the construction safety management knowledge.

Since developed Construction Safety Ontology intends to be extendable, two new safety management aspects are being considered to be included into the ontology:

(1) Safety risk factor [89] can be integrated into the ontology schema by adding it to the job step as a property, then it can be used to assess and compare different construction methods and sequences. This assists construction managers to select the safest solution. In addition, the risk assessment results can be visualized in BIM using color codes. This can become a useful tool for safety inspector who needs to identify and resolve hazards on the construction site. Preliminary results can be found in Collins et al. [27].

(2) Construction workspace conflict detection [88, 90, 47] has the potential to be solved in BIM if workspace information and parameters can be included in the Construction Safety Ontology, which will be further explained in Chapter 6.

In terms of the IFC exchange format, the current scope of *IfcConstructionMgmtDomain* schema focuses on schedule, cost and quantities of the project without considering construction safety aspect. Since the aim of IFC is to provide support for information exchange and sharing within computer aided management applications, safety is first in construction management. Technology-based safety solutions need to be developed [43] taking advantage of computer-aided approaches that replace or assist traditional management practices. It is crucial to extend the existing IFC schema to include safety prevention methods, requirement, and risk factors in the long run for creating an integrated safety management system.

3.7.2 Conclusions

This chapter presented an ontology-based semantic modeling of construction safety knowledge framework. A Construction Safety Ontology was developed to formalize the construction safety knowledge to enhance construction safety management by improving the potential of knowledge sharing and reuse. Also, it assists to sustain the safety knowledge within an organization such as sub-contractor. Interview and survey with construction experts were conducted to evaluate the structure and content of developed ontology.

CHAPTER IV

FALL HAZARD IDENTIFICATION AND PREVENTION

This chapter presents an automated rule-based checking system for BIM and how future safety planning can be integrated in work breakdown structures and project schedules. The framework and methodology for the proposed rule-based safety checking system and rule checking process are presented. The safety rule interpretation and rule-based algorithms platform for fall protection are also explained. A case study is presented to demonstrate the capability and effectiveness.

4.1 Introduction

40% of worker fatalities in the construction industry involved incidents related to falls from height [52, 106]. Inadequate, removed, or inappropriate use of fall protection equipment contributed to more than 30% of the falls [54]. A case study by Frijters and Swuste [40] demonstrated that awareness of safety during design can influence the risk of falling.

As these statistics indicate, safety in construction remains a major problem. The sad reality of frequent loss of life, injuries, near-misses, and collateral damage is that they pose liabilities that can be prevented. Safe construction requires care and planning throughout the project life-cycle, from design, through construction planning, through construction execution and extending into operations and maintenance. As good safety practices and records create a positive, hazard free, and productive work environment, planning for safety at the front-end of a project is not only the first but also a fundamental step for managing safety [109].

Failures in hazard identification are often due to the limited expertise or oversight of engineers or safety staff when planning or executing safety practices, or poor training of construction staff. Examples are tasks in design for safety, safety inspection, and monitoring safety. Failure in any of these can result in increased risk of exposing workers to hazards in the construction environment.

This research takes advantage of the potential that BIM offers for safety in construction (building) design and planning, and further it facilitates the integration of construction safety and health practices in BIM. It does so by automatically detecting and eliminating hazards. It is based on the recognition that a building model and associated schedule means that the construction site changes daily, with new safety issues emerging (and others being removed) as the project progresses. Construction processes may include activity sequences that are inherently dangerous, and without proper corrective actions these activity sequences can be identified at the planning stages and corrected.

4.2 Background

4.2.1 The traditional approach of safety analysis and control

Many efforts at safety analysis and control have been based on historical safety statistics. Yi and Langford [111] analyzed historical safety records and presented a theory on safe planning by estimating the risk distribution of a project. The approach works by estimating situations of concentrated risk and then adjusting the schedule to avoid the risk peaks. Saurin et al. [92] integrated a Safety Planning and Control Model (SPC) into the production planning and control process. Three hierarchical levels were defined: long-, medium-, and short-term safety planning. Safety control and evaluation is based on both proactive and reactive performance indicators relying on percentage of safe work packages and actual accident data. A specific Construction Job Safety Analysis (CJSA) tool was developed by Rozenfeld et al. [89]. The method focused on the identification of potential loss-of-control events for detailed staging of construction activities. The assessment of the probability of occurrence for each event was determined through interviews. The goal was to predict the fluctuating safety risk levels and to support safety conscious planning and safety management. Tam et al. [97] applied Non-Structural Fuzzy Decision Support System (NSFDSS) to evaluate safety management systems and prioritize the measures with the consideration of various decision criteria, and further to facilitate more realistic decision making.

Analysis and causation of accidents and historical data provide valuable but general information for safety planning. These are, however, not sufficient to predict when and where accidents occur on unique construction projects. This has led to the advent of information technology-enabled approaches for construction safety using virtual designs and simulations of construction operations. The following section outlines some of these initiatives.

4.2.2 Information and communication technologies (ICT) for construction safety

Information and communication technologies such as Building Information Modeling (BIM) [35], Virtual Design and Construction technology (VDC) along with Geographic Information Systems (GIS), etc. have become established tools in the Architecture, Engineering, and Construction (AEC) industry. Detecting spatial conflict or congestion of construction operations is one issue addressed using 4D visualizations [67]. Hadikusumo and Rowlinson [46] adopted Virtual Reality for construction safety by creating a design-for-safety-process (DFEP) database. The VR-based DFEP tool helps to identify safety hazards based on manual selection during the building design phase. Mallasi [66] developed the Patterns Execution and Critical Analysis of Site Space Organization (PECASO). It aims at developing a methodology and tool to assist planners with the assignment of activities' in the execution workspace, as well as the identification and visualization of workspace congestion. Benjaoran and Bhokha [13] developed an integrated system for construction and safety management based on 4D CAD model and rule-based algorithms (Hazard Explorer and Safety Measure Advisor). The automated approach with hard-coded algorithms does not consider complex design parameters and the reliance on humans is still exists to check for safety rules. Kang et al. [57] proposed building a 5D CAD-based risk visualization system for visualizing construction risk degree. Qi et al. [85] devised a design for safety tool, making design for safety suggestions available to designers and constructors by formalizing collected design-for safety suggestions and checking the building model. Bansal [10] used a GIS based navigable 3D animation in safety planning for predicting places and activities which have higher potential for accidents; this allowed to link the information between the CPM schedule and safety recommendation database. The VTT Technical Research Center of Finland [95] developed a manual procedure of using BIM technology for safety planning, management, and communications. As part of the 4D-construction safety planning, VTT visualized BIM-based 4D safety railings for fall/edge protection in Tekla Structures. Zhang et al. [115] explored the integration of construction and safety management based on 4D CAD model and rule-based algorithms.

The literature shows that BIM has enabled virtual safety controls to be used to identify safety hazards. VDC has potential to simulate various stages of the construction process to help engineers, architects, and contractors to detect, visualize, and resolve risk prior to the problematic conditions arising in the project. Although the existing studies are trying to improve safety planning using ICT, none of them can support activity-level task specific hazard identification and visualization. Further automation of the tool and better visualization are new options to be explored.

4.2.3 Compliance checking in construction

One of the promising directions of BIM applications in the AEC industry is to facilitate various rule checking and simulations for evaluating building designs in the earlier phases of a project [35, 34, 62]. A rule-based checking system is defined as a piece of software that does not modify a building design, but rather evaluates it on the basis of configured building objects. Rule-based systems assist users to define and apply rules that identify conditions of importance in the model by executing them on a given model, and return the reports, which basically consist of "pass" or "fail" [34]. Design evaluation may apply to programmatic requirements, model correctness, constructability, maintenance and other aspects of the project [79]. Conventionally, design evaluation is performed manually by multiple domain-specific experts, a time consuming, expensive and error-prone process. With BIM, such simulations can be provided through automated interfaces, more quickly and reliably [35, 49, 31]. For example, a concept design model can be used for estimating spatial validation, circulation and security checking, energy consumption simulation, and early cost estimate [34]. BIM facilitates implementing various automated rule-checking systems of building design; however, making efficient and robust interfaces involves a variety of technical issues [62].

In regard of the steps of rule checking approach, Eastman et al. [34] examined several industry efforts and case studies. Efforts have been made to generalize the rule checking systems for different building types and domains, such as automated building design reviews [61]. Along with developing rule-checking software, a domain-specific language has been introduced as a language-driven approach to the rule checking and design analysis [61]. However, development expertise in rule checking systems continues to grow and new domains and functionalities are being added to the purview of rule checking.

Zhang et al. [115] introduced the integration of construction and safety management based on BIMs and rule-based algorithms based on OSHA fall protection regulations. Industry Foundation Classes (IFC)-based solutions have also been explored for fall hazards identification and prevention in construction [69]. Solibri Model Checker

[94] is one of the commercial available applications which provides rule checking capability against BIMs for architectural design validations. However, construction safety hazards identification is not realized either in such program or by existing studies. More advanced and general rule-checking solutions for construction safety need to be explored.

4.2.4 Need for an automated rule-based safety checking system

The planning and design phases provide a vital opportunity to eliminate hazards before they appear on a jobsite. Current safety planning approaches are primarily text-based, standalone, check-sheet type tools, which are accessed either via paper or through software interfaces. Inefficiencies are witnessed in the current methods utilized for processing and reporting of the safety data for decision making in construction safety and health [60]. Previous research indicates that there is a lack of responsive tools and resources to assist designers when it comes to construction safety. Technology can potentially play a key role in reducing incident rates further, once it positively influences current practices in safety planning [99, 98, 22].

Other contributions of automated safety tools in assisting safety management in construction are as follows [41]:

1. The ability to eliminate hazards diminishes as the project progresses;
2. The opportunity to include both safety regulations and best practices for comparison and combination becomes ever more limited; and
3. A better framework to facilitate the communication between contractor and designer for safety issues is needed.

4.3 BIM-Enabled Rule Checking

Since safety rules, guidelines, and best practices already exist, they can be used in conjunction with existing three-dimensional (3D) design and schedule information to formulate an automated safety rule checking system. Unsafe conditions appear, then are resolved within the construction process, as a project proceeds. The intention is to automatically identify these dynamic conditions, as the building is constructed, identifying their location in a virtual 3D space, and interactively or automatically providing solutions and visualization of protective systems to mitigate identified hazards. Such a platform can also function as a tool for providing easily accessible and understandable visualization of up-to-date progress on construction and safety over time, and in particular, to detect dangerous hazard locations on the site. The indicators of safety measures will help safety managers planning upfront for safety during the construction planning phase, as well as during construction. This includes planning safer work tasks, and monitoring the planned work tasks during the construction phase.

4.3.1 Rule-based approach

The process of rule checking is composed of four major stages [34]:

1. Rule translation stage: rule interpretation and logical structuring of rules for each application. Most rules have been written in human languages. A common intermediate way for mapping rules from natural language to computer-processable form is a table consisting of parameterized rules.

2. Model preparation stage: the necessary information required for checking. Several model view definitions [71] can be used to both specify the information needed to carry out certain rule checks, derive the needed data required for a specific type of rule checking and to extract subsets of a given building model to allow more efficient rule execution [49, 14].

3. Rule execution stage: carries out rule checking against given building models. Execution issues largely deal with the management of this in the review process.

Technically this stage involves both pre-processing and post-processing of rule checking.

4. Reporting stage: reports the rule checking results. In this stage, the system usually produces graphical reports including textual details, as well as references back to codified source rules.

In regard of these steps of rule checking approach, Eastman et al. [34] examined several industry efforts and case studies. Efforts have been made to generalize the rule checking systems for different building types and domains, such as automated building design reviews [61]. Along with developing rule-checking software, a domain-specific language has been introduced as a language-driven approach to the rule checking and design analysis [61]. However, development expertise in rule checking systems continues to grow and new domains and functionalities are being added to the purview of rule checking. This study focuses on describing the development of a new domain of rules – construction safety planning and simulation, as well as relevant issues for developing a safety checking system such as building model preparation issues regarding BIM platform, rule executions, and reporting issues.

4.3.2 Rule-based platform

A rule-based checking system can be implemented in two different ways. One way is a design based software application/plug-in that allows architect/engineers/designers to check a building model during the design process. Current available BIM design tools do not provide model checking functions themselves. An application can be developed on the BIM platform, providing ease for a designer to validate their model according to target rules without the need to change the design later. Since model and information exchanges are inevitable between different project stakeholders and during different project phases, a major issue is data interoperability. Especially, data interoperability between different BIM platforms is a key problem to industry users. The other promising approach is to use an Industry Foundation Class (IFC)-based model viewer or checker for the implementation. IFC is a public and internationally recognized industry standard for data exchange and integration within building construction industries [36]. The IFC-based application can accept design models from various BIM-authoring software. Available rule-based platforms exist that by apply rules to IFC building model data. They show a promising approach to enable broader application of rule-checking on IFC based models [61, 81]. Existing BIM tools support export functions of IFC-based models. However, IFC is a rich and redundant data-modeling schema and clear definitions for implementation are required. The IFC requirements for a safety checking application will be considerably different from that of a clash detection application. A new model view development effort addressing the requirements of safety rule checking in BIM will need to be introduced. Preliminary work on a BIM/safety-rule checker has been introduced by Zhang et al. [113].

4.4 Objective and Scope

The goal of this research is to develop rule-checking algorithms to automatically detect safety hazards and suggest preventive measures for building information models. Since falls are the most frequently cited type of fatality in construction and to limit the scope of work, fall protection is implemented as a rule-checker for BIM.

4.5 Framework and Methodology

4.5.1 Framework for the automated safety-rule checking platform

The proposed framework of a rule-based safety checking system is illustrated in Figure 10. The first step is to collect and analyze construction data including work breakdown structure, schedule, and quantities. These are typically associated with the Building Model and Schedule. Both provide some of the most important technical aspects of a project by defining the project in terms of hierarchically related, product-oriented elements, and work processes required for each building element's completion.

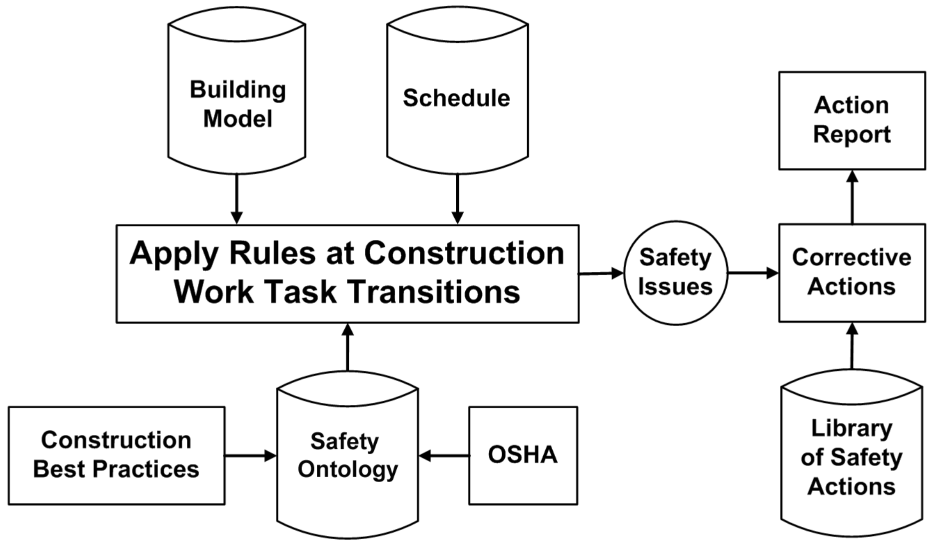


Figure 10: Framework for implementing an automated rule-based safety checking in BIM.

Each element of the WBS provides logical summary points for measuring cost and schedule performance. This information can be represented in BIM by applying the corresponding construction schedule. Compared to the traditional processes, the proposed system takes the existing Safety Rules, guidelines, and best practices (e.g., construction safety standards from OSHA or Construction Industry Best Practices) and applies them to the BIM. Safety checking rules can be applied either within a building modeling tool (for example Revit, ArchiCAD, Tekla) or alternatively within a platform that can read building models (for example, IFC platforms, Navisworks). Ideally, the rule checks are defined in a format that is portable, allowing them to be applied within different environments.

The construction site allows, and requires, extensive movement of workers from place to place [83] and so do the job activities. Since the work task transitions can potentially be the cause of hazard, the best might be to Apply Rules at Construction Work Task Transitions. For instance, when working area or job activity of a worker changes, the rule checker executes and generates new suggestions (1) to guide safety manager for specific safety inspection, and (2) to warn the worker of the potential hazards. This is doable on the rule checking side. Resolution of the safety condition often involve modifying aspects of the design, adding temporary structures or changing the schedule; these require more platform-specific capabilities. Thus, one issue is identifying stages of design manually or using the schedule to deal with work task transitions. Another issue is where the corrections are made, e.g. whether the rules are applied in the design tool or a separate checking platform. Since the building model is usually updated during the project design and operation phases, the safety checking system is connected to the system and can be re-run after each model or schedule update to ensure the planning for safety at front-end of the project.

After the developed safety rule checking system has identified the safety issues or hazards in the BIM, corrective actions, such as design for safety and safety planning, can be conducted. The goal of the rule checking system is to assist human decision makers in the safety planning and scheduling by proposing realistic solutions to resolve the identified issues. A library of safety actions proposes corrective actions that can be taken to avert the identified hazards. Multiple alternative actions may be stored to respond to a single safety condition. The solutions should have correct geometry, location, materials and time of installation of the protective equipment that must be installed to avert a hazard, or that alternatives are proposed to modify the work tasks. A big challenge for reflecting safety in design is that scheduling is usually not considered until design is almost complete. The rule checking results can be communicated to the designer along with corresponding safety requirements from the contractor through an action report. Identified hazards can be eliminated at the front-end of projects or during construction, if necessary.

A transformative step in the industry would be to integrate safety into the design process and to start scheduling for safety earlier. This facilitates safer design and shortens the iteration loops, since the designer is able to modify the model directly after checking the results. The use of the design for construction safety concept may gain momentum especially in Design-Build (DB) or Integrated Project Delivery (IPD) project delivery methods [11], as there is more scope for interaction between the designer and the contractor at an early stage of the project. The safety knowledge is transferred from the contractor to the designer based through the checking results. And the system can present the stored alternative resolutions, or automate the corrections, controlled as a "safety style" to respond to the identified conditions in a particular way.

Then, after model update and safety re-check, the system is used by the contractor for normal safety planning. According to OSHA/best practices, solutions or prevention methods vary by the application case. Since a review of all rules and guidelines would be too consuming, a user typically selects a safety plan from a known repertoire of available solutions.

4.5.2 Automated safety checking process

In view of this, safety planning is implemented in two steps: a user can (1) define and run the checking by applying default prevention method automatically first and (2) provide possible protection alternatives including different safety protective system for customization. As a result, the proposed rule-checking platform aims to assist in the decision making process and the final decision can be left with a safety engineer, although after a while we expect that the corrections also will become automated. Safety personnel can consider and concentrate on other factors in the decision making process (e.g., checking of suggested protective system, availability of protective system, lower cost alternatives).

Thirdly, the rule checking system generates safety reports. At the operational and monitoring stage of a project, automatic reports in table form can guide the installation of protective equipment correctly and in a timely manner. They can also be used to document safety issues and become part of the legal project obligations. Rather than performing safety inspection based on experience, a safety manager who needs to conduct site inspection everyday can use the reporting features to ensure that safety implementation strictly follows the designed safety plan.

4.5.3 Rule checking development process

The rule checking approach is further illustrated in Figure 11 and explained as follows:

1. Rule interpretation: The interpretation of safety rules from safety regulations or best practices (e.g., OSHA) is logic-based mapping from human language to machine-readable format. The name, type, and other properties in the rule can be analyzed and extracted from the rule. The rules can then be classified in differing site conditions using IF-THEN context to determine the corresponding measures. Rule translation typically has two aspects: (a) the condition or context where the rule applies and (b) the properties upon which the rule applies. The first step might identify the target building object for example a slab, and the second step would then check the width, length, location, etc. of the identified slab. The interpreted rules are stored internally in the rule checking system, while the conditions applying the rules can be customized by users on system interface.

2. Building model preparation: In object-based modeling, all building objects should associate with specific object type and attributes. This information is used as the basis for checking geometric features. Thus the requirements of a rule checker for building models are stricter than existing 2D drawing or 3D modeling requirements. Compared to existing BIM application such as clash detection and BIM-based quantity takeoff, a basic requirement for a rule-based checking system is that each building object carries information such as name,

type, attributes, relationships and metadata including id, means of creation of the model elements, time and data of creation and etc.. Schedule data need to be linked to the building object since the assigned protective system needs to be updated accordingly. In addition, the spatial structure to each building object needs to be well organized; for example, by floor or section. This helps to classify the model and space constraints more easily. In summary, a parametric model is a necessary condition to extract the required values for the next step: rule computation.

3. Rule execution: The rule execution phase brings together the translated rule sets and the prepared building model. Since the rules have been transformed in machine readable code, their executions are straightforward. The building objects can be mapped to the rule sets by name, type, or other attribute(s). Complex algorithms may be required for performing customized safety checks. These then semantically match the work tasks and the building objects involved in the work task and site conditions. Providing a variety of both building project and safety protection methods, the rule execution is designed to have two steps: (a) automatically check the model and apply safety measures according to default settings/suggested solution, and (b) provide all possible solutions which can be selected or changed according to an individual best practice after automated checking or select the best one, based on another set of contextual rules. The rule execution process is repeated to identify any new potential hazards after implementing one of the possible solutions to the first identified safety hazard.

4. Rule checking reporting: The results of safety checking will be reported in two different forms: (a) visualization of applied safety protective equipment, and (b) table-based check of the results showing detailed information from model and

the applied solution. In addition, quantity-take-off information for resource leveling of safety equipment (bill of materials) and importing the generated information into project schedules is also possible.

5. Safety correction: Since the prevention methods can be visualized, they engage human decision makers through a three-dimensional immersive environment. Such BIM views can enable better decision-making and increase the awareness of project participants, including workers, for example, in pre-task planning or daily meetings. The primary corrective actions that will take place on job sites are to schedule and track logistical movements of (safety) material based on rule check reports. An implementation in the field, for example, could be reports on a BIM platform that assign work tasks to install/remove safety equipment on a building floor.

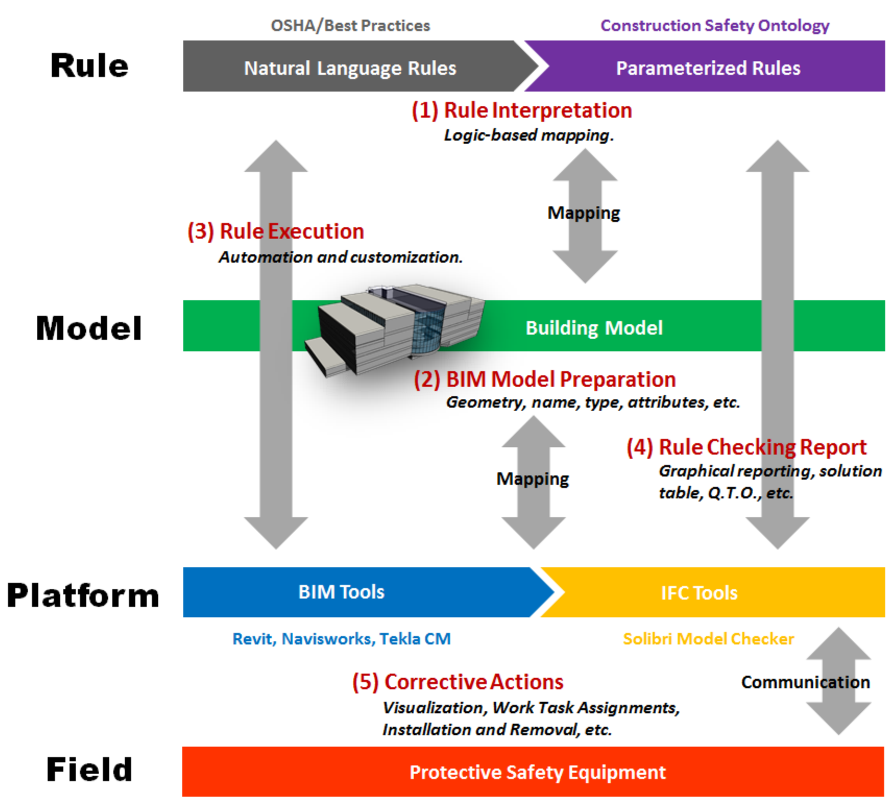


Figure 11: Rule checking process for rule-based safety checking system.

4.6 Development of the Automated Rule-Based Safety Checking System for Fall Protection

The safety rule-checking framework introduced in this study is designed to be extensible to add new safety-checking modules in the future. Since falls are the most frequently cited type of fatality in construction and to limit the scope of work, fall protection was implemented as a rule-checker for BIM. The following sections illustrate the development of a safety checking system for fall protection based on the framework introduced in the previous section.

4.6.1 Object-oriented interpretation of safety rules

According to OSHA regulations [75], fall protection rules can be classified into three parts: (1) definition, (2) general requirement, and (3) prevention criteria. Definitions specify the unsafe area. General requirements show the protection methods, which should be applied in a specific scenario. Prevention criteria relate to the detailed information of the prevention system to be used. In addition, safety checking rules need at least three components: (1) the objects, attributes and relations needed to represent a safety condition, and (2) the logic for carrying out the assessment. Once a safety condition is identified, a third aspect comes into play: (3) how to resolve the safety issue. An initial set of rules was generated using a set of fall protection rules from OSHA. A more comprehensive open source repository, customized for organization-based safety rules and regulations can be extended in the future.

The research focused on potential fall hazards, such as holes in slabs, unbounded leading edges on a floor slab, and wall openings. According to OSHA (see Figure 12) a “slab hole” means a gap or void of two inches (5.1 cm) or more in its least dimension. A hole can exist at several heights, for example, on a floor (e.g., concrete slab), a roof (e.g., skylight), or any other walking/working surface. Similar rules exist for openings in walls, for example, unprotected windows. Regardless of the size of the hole or opening, the rule-checking system automatically identifies and implements a default fall arrest system (e.g., guardrail system for edges on slabs or for openings in walls), if the location of the object was elevated more than 1.8 meters (six feet).

The following describes a few specific cases on how the rule checking algorithm works. For holes on a floor measuring more than a pre-defined value, for example 1.5 meter (59 inches), in its least dimension, the algorithm should be designed to apply a guardrail system. Whereas, holes should be "covered" if an opening measured less than one meter but more than five centimeters in its least dimension. Holes with less than five centimeters (two inches according to OSHA) in its least dimension can be ignored (due to the small size of the hole and lower likelihood objects falling through). The default table-based safety rule translation for fall protection is shown in Table 5.

*"**Hole** means a gap or void 2 inches (5.1 cm) or more in its least dimension, in a floor, roof, or other walking/working surface." (OSHA 1926.500(b))*

*"**Holes.**" Each employee on walking/working surfaces shall be protected from falling through holes (including skylights) more than 6 feet (1.8 m) above lower levels, by personal fall arrest systems, covers, or guardrail systems erected around such holes (OSHA 1926.5015(b)(4)(i)).*

Figure 12: Example of rule simplification (29 CFR 1926 OSHA) for fall protection (Green = Building objects; Orange = Object attributes; Red = Prevention systems)

Table 5: Example of table-based rule translation for holes in concrete slabs.

Least Dimension (x) of a Slab Opening	Prevention Method
< 2 inches (5.1 cm)	"Not considered"
2 < x < 59 inches (5 < x < 150 cm)	"Cover"
> 59 inches (1.5 m)	"Guardrail system"

Then, these OSHA fall protection rules are interpreted into SWRL rules based on Construction Safety Ontology:

Hole(?h) ⋀ hasWidth(?h, ?w) ⋀ hasLength(?h, ?l) ⋀ swrlb:greaterThan(?w, 2) ⋀ swrlb:greaterThan(?l, 2) ⋀ swrlb:lessThan(?w, 59) → needSafeGuard(?h, Cover)

(SWRL Rule-SlabHole1)

Hole(?h) ⋀ hasWidth(?h, ?w) ⋀ hasLength(?h, ?l) ⋀ swrlb:greaterThan(?w, 2) ⋀ swrlb:greaterThan(?l, 2) ⋀ swrlb:lessThan(?l, 59) → needSafeGuard(?h, Cover)

(SWRL Rule-SlabHole2)

Hole(?h) ⋀ hasWidth(?h,?w) ⋀ hasLength(?h, ?l) ⋀ swrlb:greaterThan(?w, 59) ⋀ swrlb:greaterThan(?l, 59) → needSafeGuard(?h, Guardrail_System)

(SWRL Rule-SlabHole3)

4.6.2 The rule-based algorithm for fall protection

The algorithm developed for the automatic safety rule checker for assessing potential fall hazards is illustrated in Figure 13. Nine basic steps are included rule mapping, execution, and reporting. For each specific timestamp, the algorithm first identifies and classifies slab, roof, and wall as the target objects from a building model. Different conditions are categorized according to specific geometry attributes. Safety conditions are flagged. Secondly, corresponding rules are executed and visualized for supporting decision-making. After applying and visualizing an automated version of rule checking, human input is optional to assist in the final decision making process. Finally, the checking results and visualization are updated in the BIM. Each hazard is detected and the proper protection method is shown. After the checking and visualization process ends, the safety rule checkers provides additional information with high relevance to decision makers, such as: (a) detailed count and cost data (quantity take-offs) for the required safety protective equipment such as railings, and (b) scheduling of the installation and removal of the safety protective system.

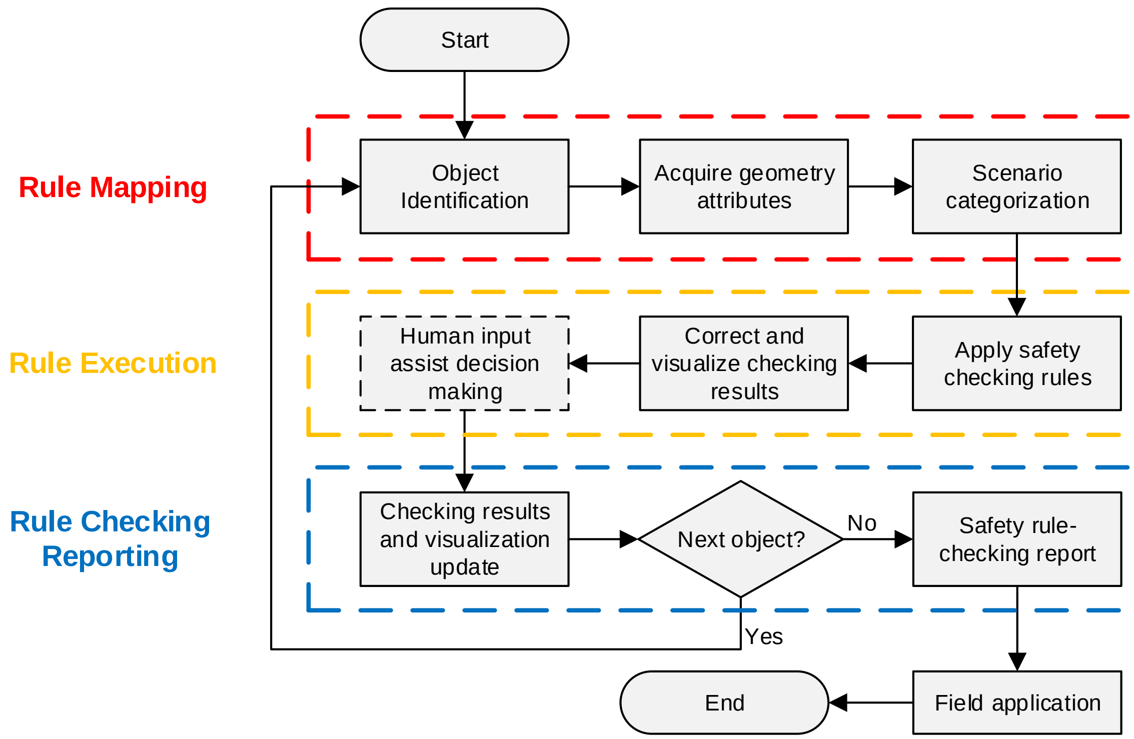


Figure 13: The rule-based checking algorithms for fall protection.

The different scenarios or contexts are determined by acquiring the corresponding spatial and geometric information of each object:

1. Slab edge protection: Figure 14 explains the algorithm for detecting required prevention methods according to OSHA safety rules. For each task, it examines if slab objects are linked to a given work task. For each slab object associated with the task, the algorithm checks if the slab needs to be merged with existing slabs. If there is no existing slab on the same level, the slab boundary is computed. Also, existing wall elements are detected to see if any part of the slab boundary does not need fall protection. Thus, unprotected edges which require guardrail protection are computed. Otherwise, existing edges,

unprotected edges, and overlapped edges are computed based on the geometry condition respectively after the slab merge. Thus, new guardrails are installed for unprotected edges and existing guardrails for overlapped edges are removed.

2. Slab hole protection: Generally, there are two methods to detect slab holes: geometry-based detection and object-based detection. Since some of the holes are cut by the designers for modeling complicated slab geometry, which should not be categorized as holes with potential fall hazards. Hence, even though geometry-based detection can find all the inner polygons of the slabs, these would include some false positive errors. For object-based detection, it requires additional labeling efforts to assist hole recognition from other void objects in the model. In this study, object-based object recognition is mainly used, then each hole is checked to see if it is a cut-through hole which create fall hazard by comparing the depth of the slab and the depth of the hole. Ideally, in order to clearly distinguish those two conditions, during the modeling stage, engineer would have two different tools/buttons to (a) create cut for complex geometry and (b) cut for actually slab cut through.

3. Wall opening protection: The wall opening detection process is similar to slab hole detection. The special situation to be considered is the location of the wall element: whether it is an interior wall or exterior wall. For the ones located at the edge of the slab, once the wall element has been installed, the guardrail for the slab edge protection can be removed, at the same time, wall opening if exists need to be protected. If there is no slab hole, for example hole for elevator shaft, close to the interior wall, the wall opening does not need to be considered or protected.

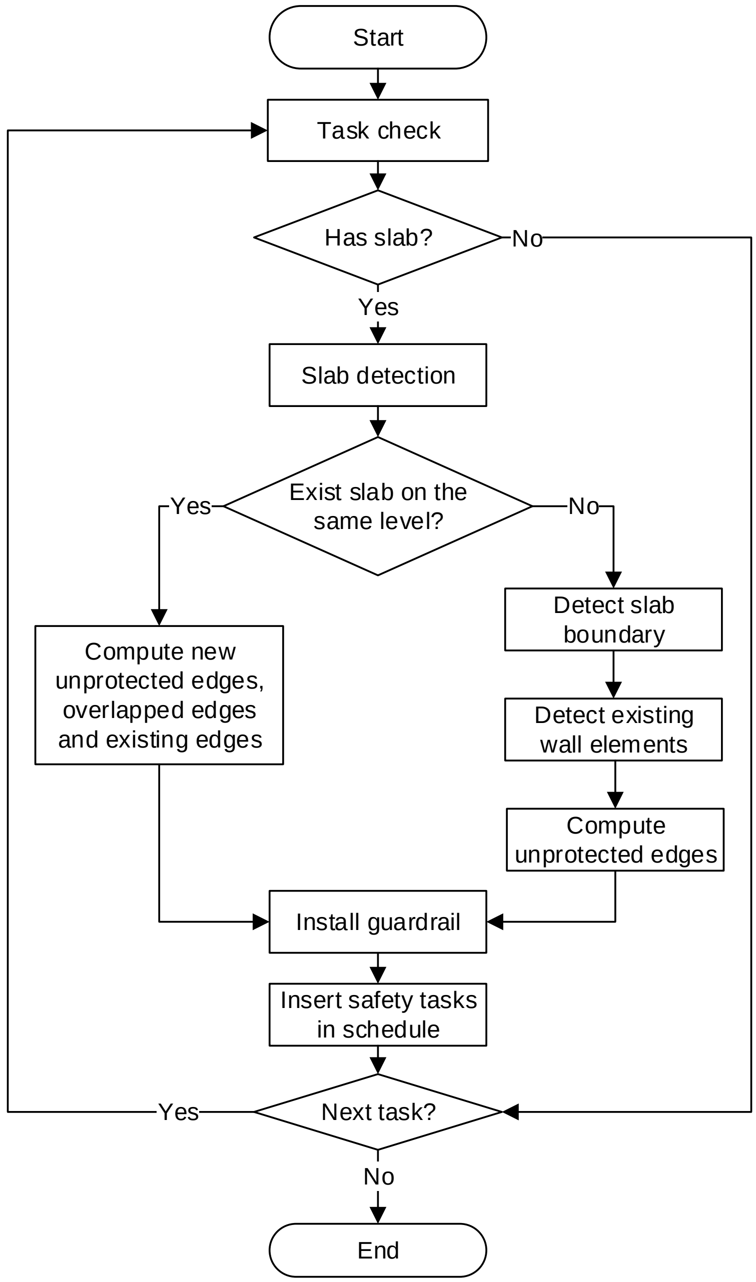


Figure 14: The rule checking algorithm for detecting required prevention methods for slab edge.

After object identification, algorithms of Step 3 (scenario categorization) and Step 4 (apply safety checking rules for checking slab/roof and wall) are explained in detail in Figure 15 and 16. The geometry of created safety equipment is based on identified unprotected opening sides. Six different cases of fall protection scenarios were identified and are listed in Figure 17.

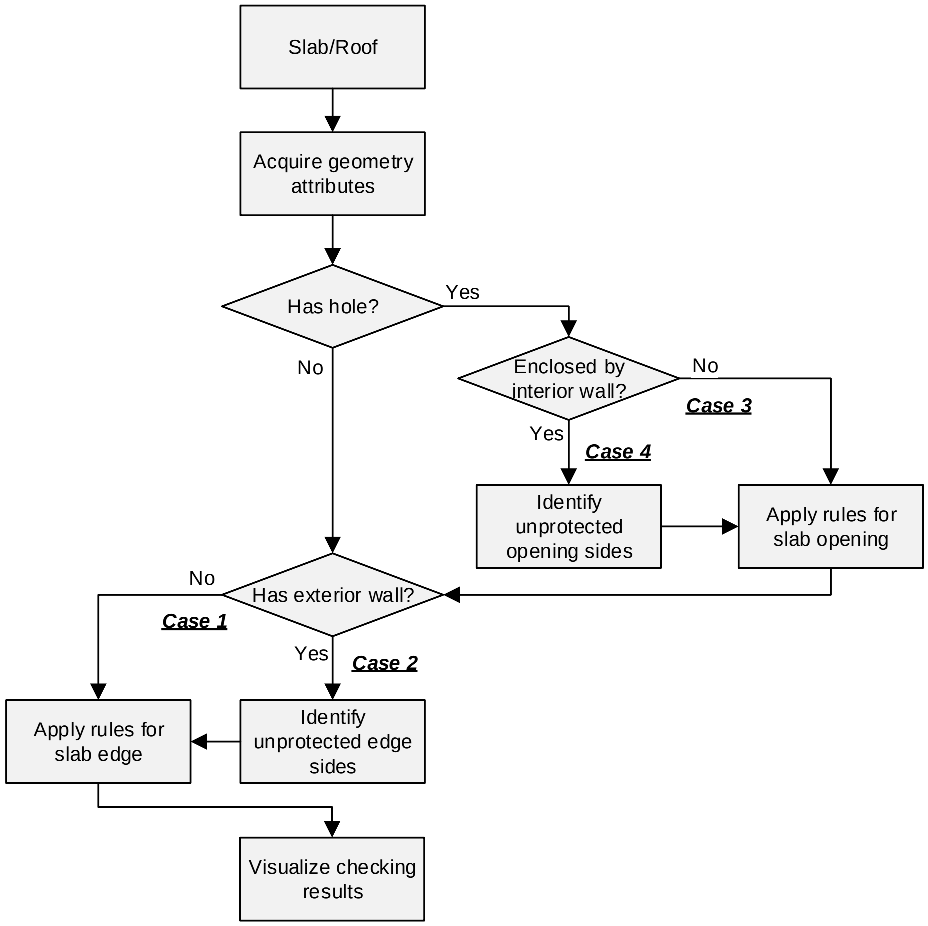


Figure 15: Algorithms of step 3 and 4: apply safety checking rules for checking slabs/roofs.

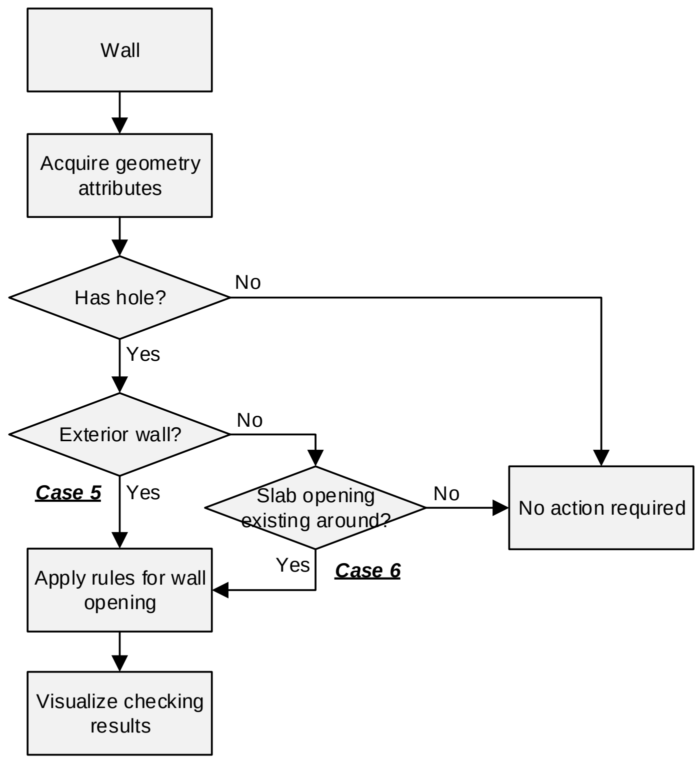


Figure 16: Algorithms of step 3 and 4: apply safety checking rules for checking walls.

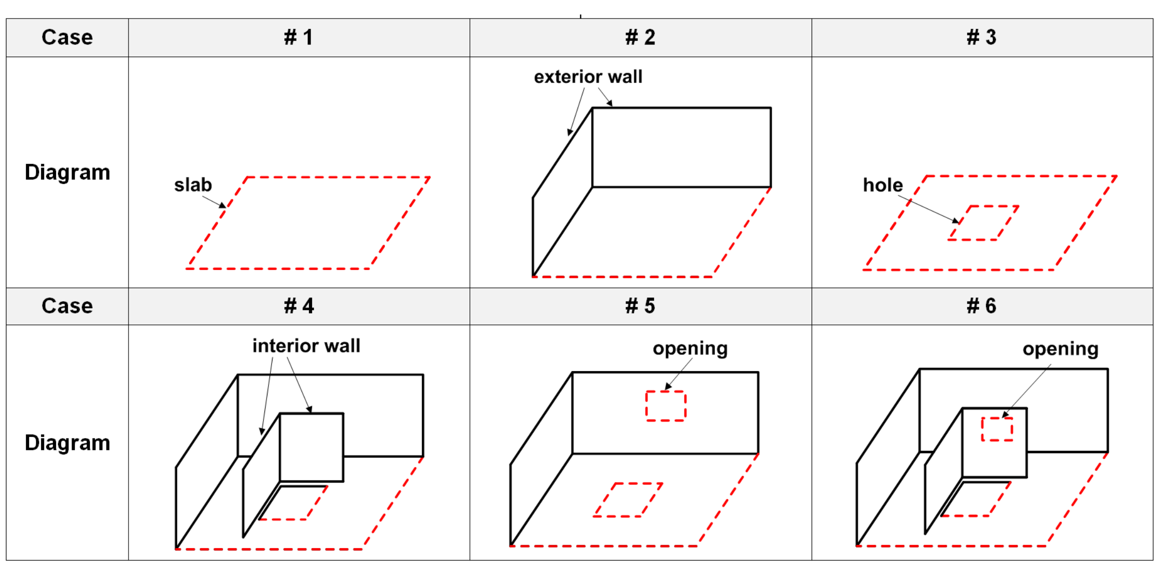


Figure 17: Cases for fall protection (edges that need protection are highlighted in red).

4.6.3 Implementation platforms

The automated rule checking system has been implemented in Tekla Structures using the open Application-Programming Interface (API). The approach allows users to check the model directly from the BIM tool.

Tekla Structures [101] is a BIM-based structural engineering and modeling software, which provides construction management functions including 4D simulation, site layout planning, and quantity-take-off functions. Syntax-based fall protection rules were converted into machine-readable equations and implemented rule-checking algorithms. The definitions of entities, relations, and properties for use in rule writing and data processing were made consistent with the data model, and were made in terms of objects, relations and properties. The implementation included the development of methods to bind the rule-checking algorithm to the building model. For example, methods were developed to derive parametric data of objects to be used for rule checking from the building model. There are two types of data processing methods implemented: (a) direct processing – is to use data directly available in the model, (b) extended processing – to use data available in the model after applying some conditions to arrive at information necessary for rule checking. An example for such an extended data processing method can be to isolate the entities in a work break down structure and based on the current status to decide if safety rules are violated in terms of dimensions and voids. If the rule checking approach utilized only data available in the model then a floor slab may not present any safety hazard, whereas if looking at the work break down structure it might involve different pour breaks for the same slab. In such a case the floor slab needs to be broken down into discrete elements on the basis of pour breaks and then fall protection rules applied. Such elaborate and inference based checking is necessary to replicate the construction sequencing into the rule engine.

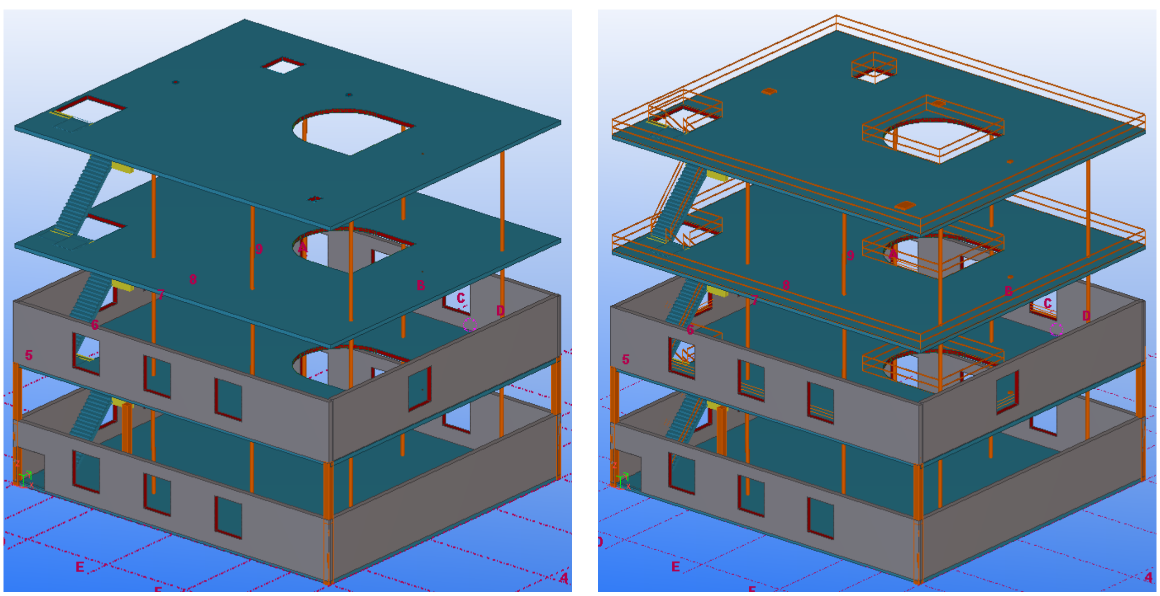
4.6.4 Future extensions using IFC

The previous sections (see 4.6.2 and 4.6.3) presented some instances of the safety rule-checking and showed that rule checking is a computationally intensive operation. To date, such safety code and parameters to check building objects in BIM for safety are not available in any commercially existing BIM software. The open APIs provided by BIM tools are limited and inefficient to handle safety rule checking issues. For extending the rules and including new types of rules and new building types, this software driven implementation is time consuming and requires extensive development. The development of a new model view needs to be studied to address the requirements for safety in BIM in the construction industry as part of future developments. If IFC is to be used as the data-modeling schema for safety rule checking applications, then the requirements have to be clearly defined. For example, IFC provides different geometric representations for objects. Boundary representations (BREP) that provide face-based solids are the most commonly used ones. However, BREPs are not sufficient to extract detailed dimensions of objects in a parametric manner. This calls for geometric representations such as extruded solid geometry. Representing semantic information using IFC involves many aspects such as required level of detail, ability of receiving application to read and infer data [107] and shall considered by researchers for future extensions of the rule checker to make it portable. Moreover, IFC schema is yet to be used for construction safety related applications. There might be a need to perform gap analysis to check if IFC can be used to represent in a sufficient manner the safety aspects. A model view definition (MVD) will help to extract all the requirements and document them in a publicly available form. This will enable software developers across the industry to conform to the requirements of safety checking to be provided as a feature in their tool.

4.7 *Case Study: Applying the Automated Rule-based Safety Checking System on BIM Platform*

4.7.1 Implementation

A test model was created in Tekla showing a construction project in progress. The model includes different types of openings representing a potential fall hazard. The identified openings have different sizes and geometric shapes (polygonal, rectangular, and circular). The holes are located in walls and floor slabs. The model (see Figures 18) shows a four-story building with walls on the first two floors. Detailed views are shown in Figures 19 and 20. Bounding box of the hole with complex boundary is computed as the base for designing safety protective equipment.



(a) Modeling without protective system (b) Modeling with protective system

Figure 18: Automated rule-based fall protection detection and installation in Tekla.

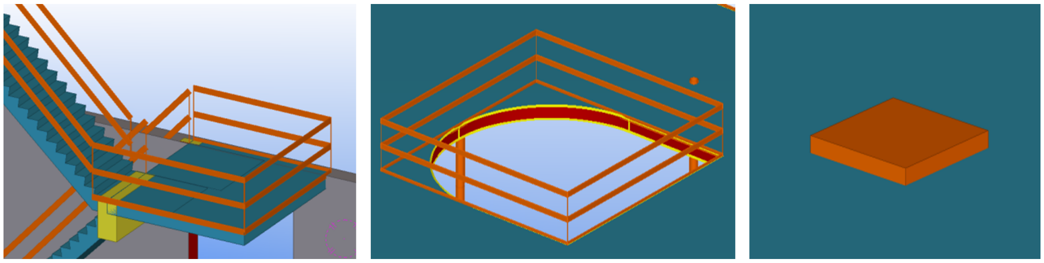


Figure 19: Examples of protective equipment for staircases, slab edges, and slab openings with different shapes/dimensions.

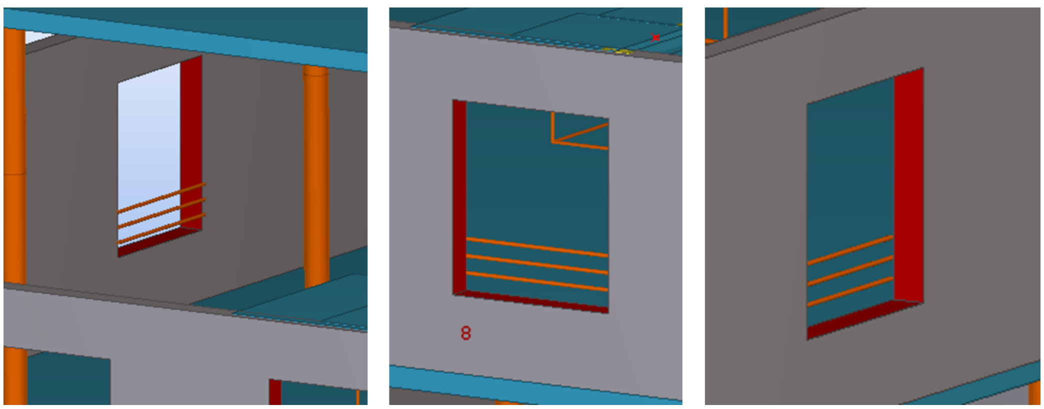


Figure 20: Examples of exterior wall openings and guardrail protection system in place.

The rule-checking steps are listed as follows:

1. Automatically check the model and detect holes in slabs and walls, and edges of slabs;

2. Install guardrail system at floor edges/slab opening/wall openings and cover slab opening;

3. Take-off quantity and type (leading to an estimate) of the protection safety system to be installed;

4. Provide an updated schedule of when and what safety protective system needs to be installed; and

5. Create a 4D visualization and 3D virtual environment to visualize the protective system and how it fits in the construction schedule/sequencing (Figure 21).

After scheduling of the building elements, the rule checker is executed for generating and inserting the schedule for related safety protective system into the schedule. For instance, Figure 21 shows 4D simulation results along schedule. Safety elements are in orange, completed building elements are in green, and elements in progess, upcoming in one week and upcoming in two weeks are colored using blue, red and yellow correspondingly. The schedule of the guardrail system which is related to both slab and walls on the second floor is determined by the end date of constructing the slab and the start date of constructing the wall. In this manner, tasks of installation and removal of that guardrail system is inserted into the schedule and corresponding guardrail system elements (including post and the handrail) are linked to the schedule automatically.

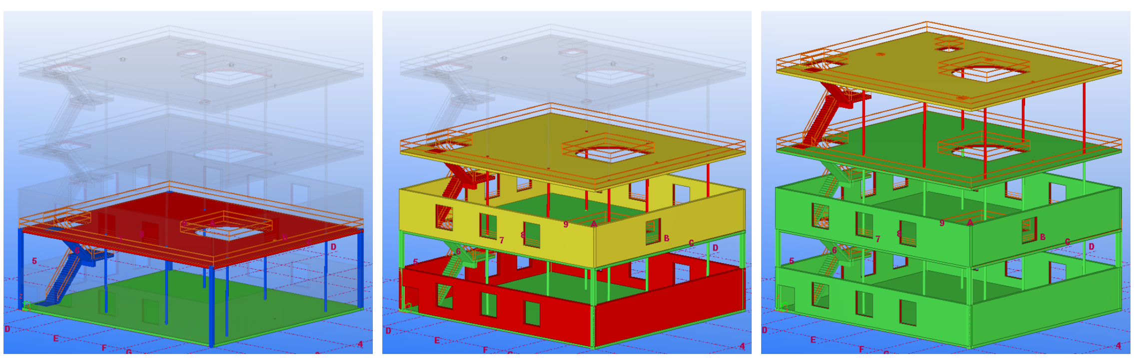


Figure 21: 4D simulation along schedule (Legend: Orange – Required Safety Equipment; Green – Completed; Blue – In Progress; Red – In 1 Week; Yellow – In 2 Weeks).

After testing the system on simple models, rule-based safety checking module was also tested on realistic and complex models from the construction industry. In the case study, the developed automated rule-checking tool was applied on a multi-storey precast apartment building model (see Figure 22). The yellow dash lines shows the three sections of the building, A, B, and C. The goal was to demonstrate safety checking results dynamically based on the project schedule. All precast concrete pieces were fabricated and transported to the construction site, and they were erected with predefined order starting from Section A, followed by Sections B and C. The façade insulation and brick walls were built on site after the precast concrete wall elements were stood in place. The project's structural model had been modeled using Tekla Structures 17.0 modeling software. The 4D schedule needed for the automated rule-checking platform was added to the structural model based on information obtained from the contractor. This information was provided by the site engineer in the traditional format of a construction schedule and work breakdown structure concerning the installation sequence.

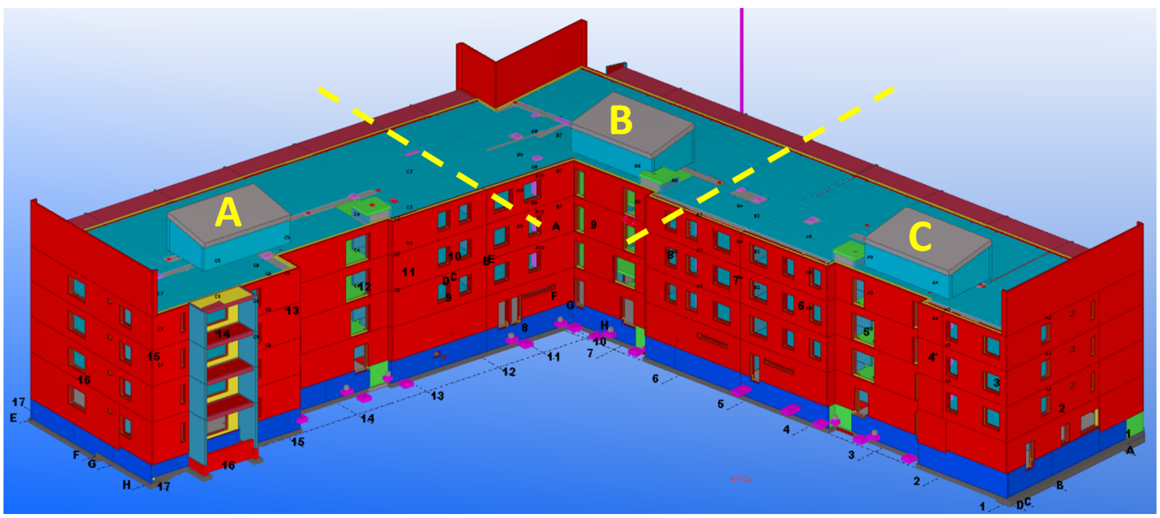


Figure 22: Overview of the multi-story precast apartment building model and its sections.

Figure 23 shows a close view of the concrete slab pieces. The slab sections were erected by story. It takes about a week to erect one story of a section and about 5-6 weeks to erect one section. After the rule checking algorithm was executed, the fall prevention system was generated and visualized in the model automatically. The algorithm also created sub-tasks for the installation and removal of safety-relevant equipment into the construction schedule. Figure 24 shows partially a comparison between the original schedule and the updated schedule with the required safety solution. The guardrail solutions need to be updated according to the growth of the slab sections. For example, when two slab sections merge on the same level the guardrail in between needed to be removed. Figure 25 shows the four different phases of the model simulation that are available to provide temporal visualization of the safety equipment embedded into the model and construction schedule.

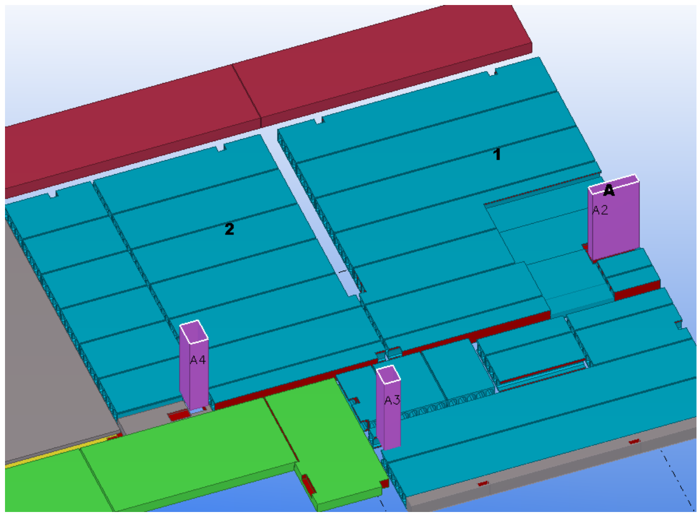


Figure 23: Close view of precast slab panels.

	Task Name	Planned Start Date	Planned End Date
1	Foundation	4/30/2012	5/4/2012
2	⊟ **Section C**	**5/7/2012**	**6/14/2012**
3	⊟ **1st floor**	**5/7/2012**	**5/15/2012**
4	Walls and Balcony panels	5/7/2012	5/10/2012
5	Staircase slabs, Stairs, Balcony slabs	5/11/2012	5/11/2012
6	Hollow core slabs	5/14/2012	5/14/2012
7	Precast ducts	5/15/2012	5/15/2012
8	⊟ **2nd floor**	**5/17/2012**	**5/25/2012**
9	Walls and Balcony panels	5/17/2012	5/22/2012
10	Staircase slabs, Stairs, Balcony slabs	5/22/2012	5/22/2012
11	Hollow core slabs	5/23/2012	5/23/2012

	Task Name	Planned Start Date	Planned End Date
1	Foundation	4/30/2012	5/4/2012
2	⊟ **Section C**	**5/7/2012**	**6/14/2012**
3	⊟ **1st floor**	**5/7/2012**	**5/15/2012**
4	Walls and Balcony panels	5/7/2012	5/10/2012
5	⊟ **Staircase slabs, Stairs, Balcony slabs**	**5/11/2012**	**5/11/2012**
6	Slab Edge Protection	5/11/2012	5/11/2012
7	Slab Hole Protection	5/11/2012	5/11/2012
8	⊟ **Hollow core slabs**	**5/14/2012**	**5/14/2012**
9	Slab Edge Protection	5/14/2012	5/14/2012
10	Slab Edge Protection Removal	5/14/2012	5/14/2012
11	Slab Hole Protection	5/14/2012	5/14/2012
12	Precast ducts	5/15/2012	5/15/2012
13	⊟ **2nd floor**	**5/17/2012**	**5/25/2012**
14	⊟ **Walls and Balcony panels**	**5/17/2012**	**5/22/2012**
15	Slab Edge Protection Removal	5/22/2012	5/22/2012
16	Wall Opening Protection	5/22/2012	5/22/2012
17	⊟ **Staircase slabs, Stairs, Balcony slabs**	**5/22/2012**	**5/22/2012**
18	Slab Edge Protection	5/22/2012	5/22/2012
19	Slab Hole Protection	5/22/2012	5/22/2012
20	⊟ **Hollow core slabs**	**5/23/2012**	**5/23/2012**
21	Slab Edge Protection	5/23/2012	5/23/2012
22	Slab Edge Protection Removal	5/23/2012	5/23/2012
23	Slab Hole Protection	5/23/2012	5/23/2012

Figure 24: (Left) The original schedule; (Right) Updated schedule with the installation and removal of fall prevention methods.

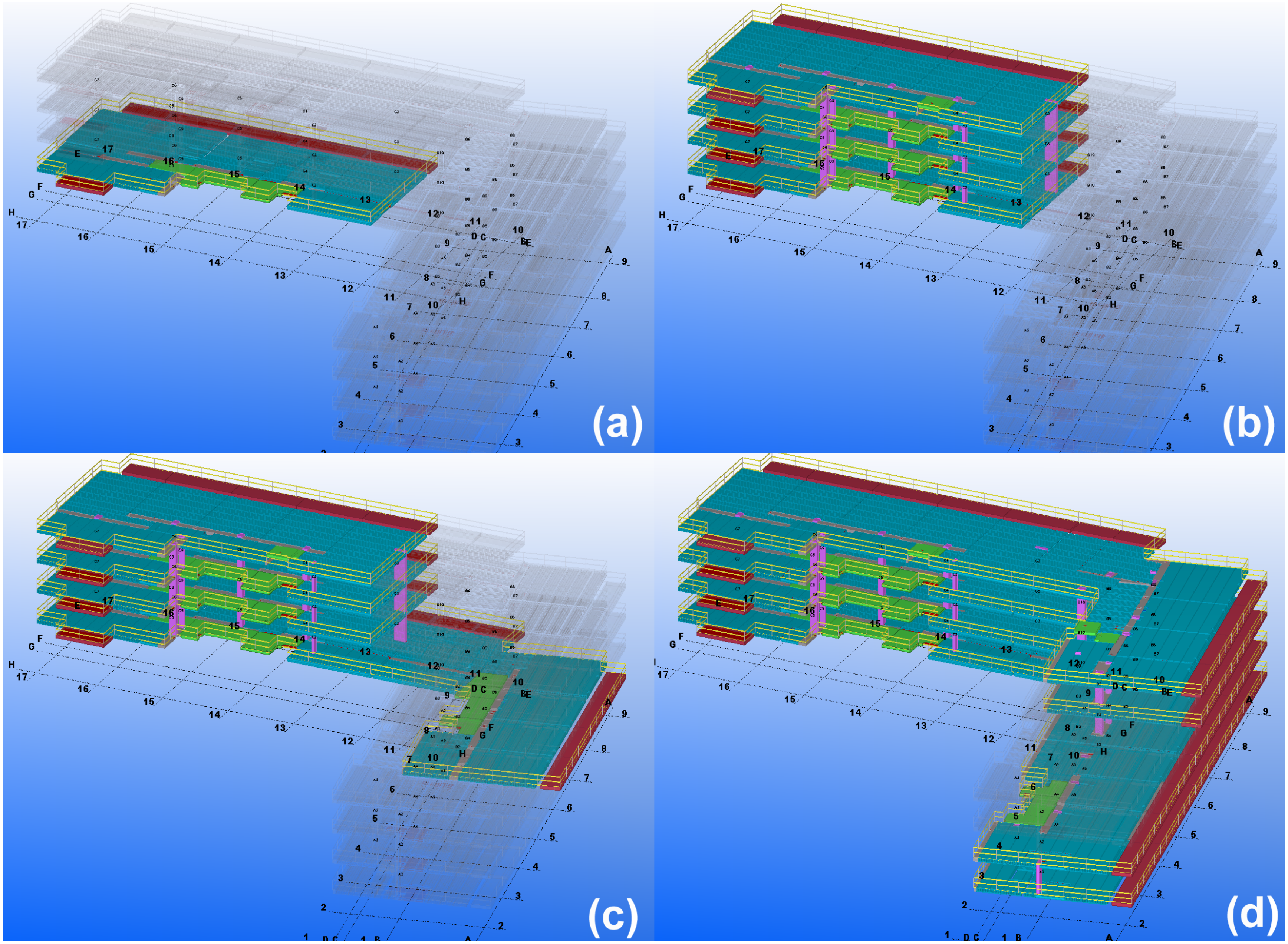


Figure 25: 4D simulation of the model slab, column, and guardrail prevention systems.

In Figure 26, the slab on the first floor grows from Section A to Section B. Since they merge at some time during construction, the guardrail in between must be removed. Removal also improves the work flow on site, since workers are now able to safely walk from Section A to B without taking any detours. The installation and removal of the building sequence is shown in Figures 25-b and 25-c.

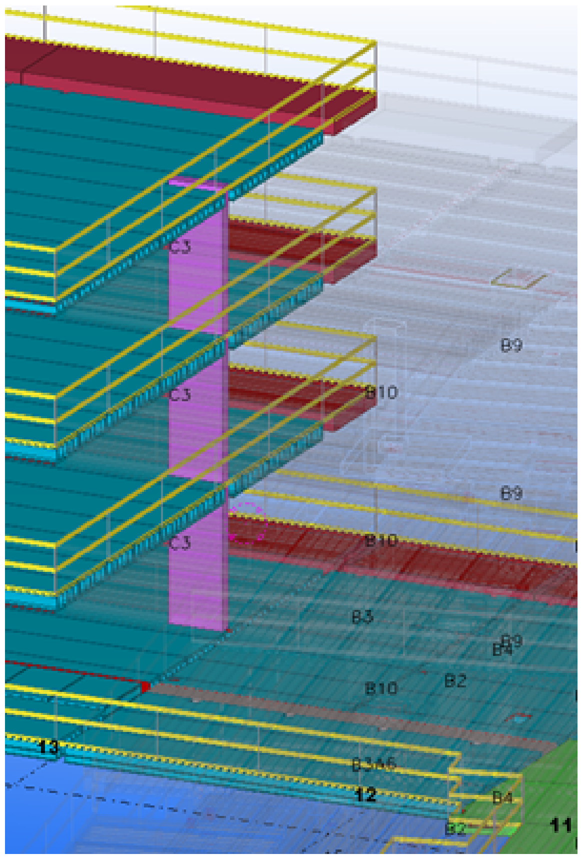


Figure 26: Close view of the connection of Section A and B

Figure 27 shows more detailed views of the slab edge protection and wall opening protection. After the generation of the safety protective system in the model, the checking report is also generated automatically. This report can then be exported into a MS Excel format as shown in Figure 28. The last column of the table can be used as a tool for superintendents to check the installation of the protective system in the field. Such file formats offer field safety or superintendent simplified use of the generated data. They can, for example, calculate the required safety equipment that is needed to protect the work site. Eventually, the list may also support the pre-fabrication of detailed safety solutions that can be pre-fabricated offsite and installed in similar ways as customized precast concrete panels. Thus the developed tool and the data it generates support multiple Design-for-Safety (DfS) concepts. Such a list can also be used as an inspection checklist to make sure all the required protective safety systems have been put in place on the construction site.

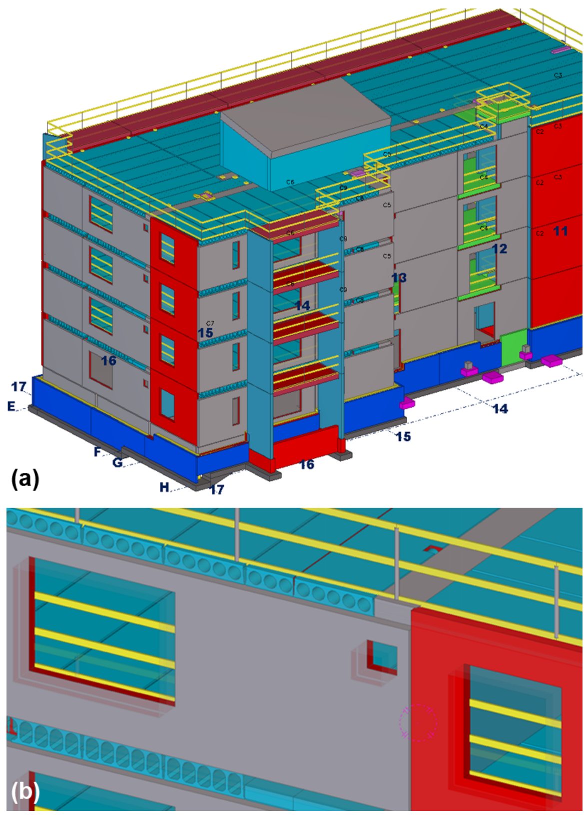


Figure 27: Protective fall protection systems in Section C of the building (left) and close view of wall opening protection (right).

Slab Hole Checking Results								
Project Name:				Analyst:			Date: 1/28/2013 2:36:10 PM	
No.	GUID	Level	Distance to Lower Level (mm)	Length (mm)	Width (mm)	Area(m2)	Prevention Method	Check
1	2301919	1	3185	235.86	235.86	0.05	Cover	FALSE
2	1862884	1	3185	110	150	0.02	Cover	FALSE
3	1845126	1	3185	200.01	120	0.05	Cover	FALSE
4	1807649	1	3185	200	200	0.04	Cover	FALSE
5	1808525	1	3185	270	180	0.05	Cover	FALSE
6	1808623	1	3185	200	200	0.04	Cover	FALSE
7	1808591	1	3185	260.91	200	0.05	Cover	FALSE
8	1808719	1	3185	200	200	0.04	Cover	FALSE
9	3390930	1	3185	942.25	614.51	0.09	Cover	FALSE
10	1862931	1	3185	150	110	0.02	Cover	FALSE
11	3390851	1	3185	460	305.03	0.17	Cover	FALSE
12	3390827	1	3185	610	390	0.23	Cover	FALSE

Figure 28: Bill of materials: Slab hole checking results provide an Excel sheet for estimating and prefabrication of safety equipment.

The user-interface for slab hole checking is shown in Figure 29. Users can define their own requirements in terms of different prevention methods using the tool's interface. After the rule execution, safety protective equipment will be visualized in the model and also checking results will be listed in a separate dialogue, from which safety manager can preview the results and make changes manually if necessary. This keeps a human decision maker in the loop of protective safety hazard detection and prevention.

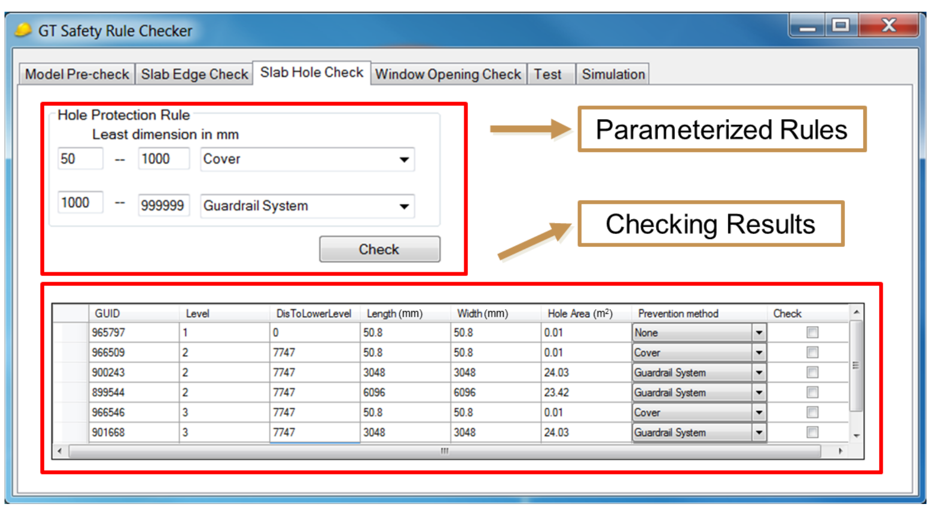


Figure 29: Slab hole checking user-interfaces.

4.8 Conclusion and Discussion

4.8.1 Discussion

Limitations of the safety rule-checking system were found through case studies and implementation in building information models. These are: (1) since the environment of construction sites is changing constantly, it currently cannot represent all unsafe conditions in a BIM on a real-time basis and (2) a manual effort in rule interpretation is now required both in terms of rule translation into machine readable code in the selection of corrections of needed to select the best correction of an unsafe condition.

This work also shows that the requirements for a safety checking system are different from that of a traditional BIM tool. Like most forms of analysis or evaluation, BIM platforms must be tuned and specific model requirement must be supported for addressing safety issues. The method and algorithms introduced in this research were for addressing fall protection. Many other areas in safety and health exist that also require similar attention. For example, human factor engineering requirement or safety in design requirement can be automatically checked in the model to make sure there is enough and safe space for operation and maintenance [116].

The developed tool detected unprotected slab edges and installed required guardrail system both automatically and successfully. Quantity-take-off of the guardrails can be easily calculated using the BIM software's built-in function. In addition, the automated installed guardrail for slab edges and window openings can be modified by a user later manually.

During the test trials, a detailed 3D model for so-called hook posts was successfully integrated in the tool (see Figure 30). A user is now able to select a simplified model representation or a detailed representation (custom components) for safety railing modeling. In addition, more detailed guardrail models and related safety equipment parts and components, such as welded fittings, could be added and modeled automatically into steel beams or concrete panels for guardrail installation. The corresponding connections can be pre-considered in the steel beam or concrete panel fabrication, hence reduce the work at height. However, if a user's goal is to provide detailed and automated safety modeling, a program needs to be developed much further to improve the rules for post positions as well.

Currently, a rough fall prevention plan is created using the developed prototype tool. An additional area for future research is generation of process flow maps and the role of safety engineers, specialists, and inspectors as they should take full advantage of BIM-based enabled safety hazard detection prevention planning tools.

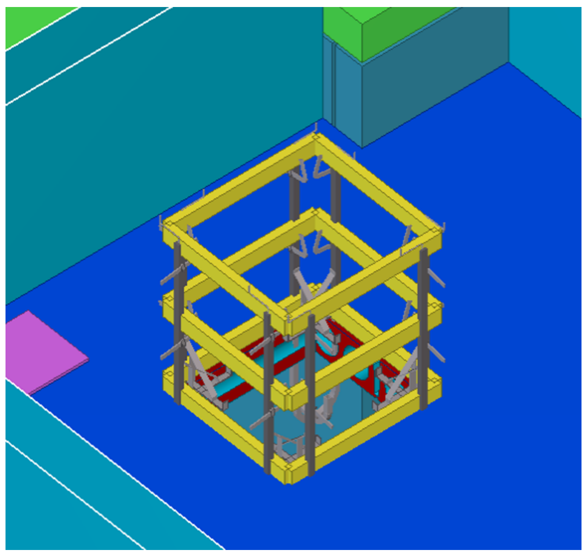


Figure 30: Realistic and detailed guardrail representation.

Potential future areas of improvement based on the findings from the conducted test trials are:

1. Providing high level of the detail to safety elements: Guardrail posts and boards, for example, can be visualized in a BIM with abstract lines. An inexperienced user might prefer high level visual detail of what the posts look like, and in case anchors are needed, which exact location these need to be placed on a concrete surface. An experienced user indeed may be interested in high level of detail for additional functionality, for example, when certain safety equipment can be

pre-fabricated. Knowledge of complex connections between guardrail posts and building components may accelerate the installation process of such components in the field.

2. Using software independent data exchange formats: Software independent data exchange formats facilitate easier communication among multiple project stakeholders. An IFC-based solution needs to be explored for safety planning purposes. The ability to use an IFC model for automated safety checking and planning will allow more general checking capability of models created in various BIM authoring tools.

3. Testing on complex models: In the future, more comprehensive BIM-based fall prevention planning solutions need to be tested on complex model geometry and provide high level of detail with the entire range of safety solutions. For instance, installing alternative solutions such as safety nets, hooks to tie-back during construction as well as during facility operation and maintenance.

4.8.2 Conclusion

This research outlined a framework for a rule-based checking system for safety planning and simulation by integrating BIM and safety. Potential safety hazards can be automatically identified and corresponding prevention methods can be applied in an automated approach.

New algorithms and methods were developed to automatically analyze a building model for safety hazards and derive the required parametric data in order to apply the safety rules. The automated rule-based safety checking system has been successfully implemented both on sample models and on a real model for fall protection. The performed research illustrates that safety planning can be considered in the scheduling stage for early detection and application of a protective safety system integrated in BIM, including identification of hazard location, quantity take-offs, and schedule for implementation of protective safety equipment. From a safety management perspective, time and effort of safety staff/engineers can be saved through an automated safety code checking and simulation tool that assists labor-intensive safety checking tasks. For example, hazardous work spaces can be identified and potential hazards can be prevented at the design stage, before any field work is started.

CHAPTER V

AUTOMATED JOB HAZARD ANALYSIS

JHA is a technique that focuses on job tasks as a way to identify hazards before they occur. This chapter presents an automated JHA framework to enable early hazard identification and BIM-based visualization. Detailed descriptions of how instances/individuals are generated based on both ontology and BIM, and how associated safety knowledge can be inferred by defining rules of logic are presented.

5.1 Introduction

About 90% of workplace injuries can be traced to unsafe work practices and behaviors [102]. As good safety practices and records create a positive, incident free, and productive work environment, planning for safety at the front-end of a project is not only the first but also a fundamental step for managing safety [109]. Planning for safety typically consists of the identification of all potential hazards, as well as the decision on choosing corresponding safety measures [10]. A job hazard analysis (JHA) is a technique that focuses on job tasks as a way to identify hazards before they occur. It focuses on the relationship between the worker, the task, the tools, and the work environment [21]. As a process of identifying potential hazards for each step of an activity and proposing safety rules to prevent potential incidents related to these hazards, the US Occupational Safety and Health Administration (OSHA) recommends performing JHA for construction activities to highlight and react to potential hazards. The basic procedure (see Figure 31) for conducting a JHA includes (1) identifying all job steps of a given activity; (2) identifying potential hazards related to these different job steps; and (3) proposing action procedures (e.g., safe procedures or precautions) to eliminate, reduce, or control each hazard [72]. Table

6 shows a sample JHA form of an activity “Strip column”. It lists general project and task information, the type and the actions to control the hazards. The JHA form is typically read and explained to workers in a pre-task work meeting. Each participant is required to acknowledge its content by signing the form. This ensures that each worker is familiar with related work task hazards and mitigation strategies. Beyond such advantages alerting workforce ahead of executing potentially dangerous work tasks, some project stakeholders may use the form for legal purposes.

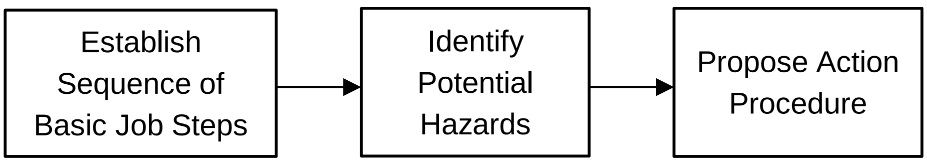


Figure 31: Basic JHA procedures

Table 6: Sample JHA form

Project Title: *GT EBB*	**Job Location:** *Fifth Floor*	**Analyst:** *Safety Superintendent A*	**Date:** *Nov. 17, 2013*
Activity Name: *Strip column*			
Job Step: *Break formwork loose*			
Hazard Type: *Unexpected formwork release*			
Hazard Controls: *1. Barricade off the area to be stripped. Only authorized personnel and equipment are allowed in the stripping area* *2. Make sure there is proper lighting* *3. Have a coworker hold the form from falling* *4. Clear all concrete and loose material from formworks to prevent anything from falling overhead during stripping*			

Because of the complexity and time-consuming nature of JHA, safety personnel need extensive time to acquire the JHA information and then apply the knowledge to perform the analysis. Another factor contributing to the time-consuming nature of JHAs is the one-of-a-kind character of construction projects which makes each JHA unique. However, the entire analysis is typically structured in multiple stages containing a number of recurring and similar JHA. Such JHA can be represented and stored as generic reusable patterns that can be standardized and instantiated for many different projects.

With the advancement of information technology in the building and construction industry, a missing link between safety management and information models becomes apparent. The richness of design information offered by BIM has helped on the delivery of better quality buildings. The ability to extract construction specific information from a BIM is critical to support productive, safe and healthy construction workplaces and other downstream processes [73]. In terms of construction safety, the current construction safety information and knowledge available through mandated safety rules and regulations, existing accident records, and personal safety engineering experience are mostly scattered and fragmented. It currently cannot easily be linked to or represented in project models such as a BIM. Given these circumstances, this research presents the development of an automated JHA application based on the Construction Safety Ontology to to enable early hazard identification and BIM-based visualization.

5.2 Background

5.2.1 Traditional JHA practice

The complex and dynamic nature of the construction industry and its on-site work patterns are widely recognized. Safety planning in unstructured construction environments is thus more challenging. Traditional JHA requires safety personnel to perform several important tasks, for example, learning from historical documentation to gain safety knowledge and applying it to activities on new construction projects. The individual nature of activities can lead to problematic JHA and expose workers to hazards. Hence, JHA is complex, time-consuming, at times inaccurate, and hard to keep up-to-date with changing construction schedules. Safety personnel must perform JHAs often weeks, sometimes even months, before the activity actually is scheduled to be performed [110]. This makes it difficult to quickly react to changes in the construction plans and schedules while appropriately managing the resulting safety concerns.

5.2.2 Information technology supported construction hazard identification

Information and communication technologies (ICT), such as BIM, Virtual Design and Construction technology (VDC) along with Geographic Information Systems (GIS), have become established tools in the Architecture, Engineering, and Construction (AEC) industry. A number of research efforts focused on improving construction hazard identification using ICT. Hadikusumo and Rowlinson [46] developed a design-for-safety-process (DFSP) tool to assist a user in identifying safety hazards inherited within construction components and processes. The DFSP database contains object types, possible safety hazards, and accident precautions database. Bansal [10] uses GIS based navigable 3D animation in safety planning for predicting places and activities which have higher potential for accidents; he links the information between the CPM schedule and safety recommendation database. The VTT Technical Research Center of Finland [59] developed a job safety analysis method with the aid of virtualized construction site using CAVE (CAVE Automatic Virtual Environment) [30]. Guo et al. [45] developed a conceptual framework of adopting virtual prototyping technology to aid construction safety management. It consists of three components: modeling and simulation, the identification of unsafe factors, and safety training. Lin et al. [64] developed a 3D video game, Safety Inspector, to provide a comprehensive safety training environment in which students assume the roles of safety inspectors and walk the game site to identify potential hazards.

The literature shows that VDC has potentials to simulate various stages of the construction process to help engineers, architects, and contractors to detect, visualize, and resolve safety hazards prior to the hazardous conditions arising in the project. Although these existing studies share similar objectives with this study, none of them can support task specific hazard identification and visualization on the activity-level.

Further automation of the process and better visualization methods need to be explored.

5.3 Objective and Scope

This research aims to propose a framework to automate the project-based JHA process of construction and provide BIM-based visualization. The proposed framework integrates Construction Safety Ontology with BIM. To limit the scope, this research focuses on concrete construction activities due to their high frequency and severity of incidents and injuries. According to the report of the Bureau of Labor Statistics (BLS) [105], poured concrete foundation and structure construction contractor has been recognized as one of the most high-risk specialty trades. While the possibility to connect the ontology to BIM is explored, the actual semantic modeling of safety information in the form of building information using, for example using IFCs, is not investigated in this research.

5.4 System Architecture

The system architecture of ontology-based hazard identification application includes ontology editor, reasoner, rule engine, and BIM platform (see Figure 32):

1. *Protégé* is an open-source platform to construct domain models and knowledge-based applications with ontologies [70]. The owl-based safety ontology is first modeled and edited using *Protégé* to define its classes, relationships and axioms.

2. *Pellet* is an OWL 2 reasoner providing OWL Description Logic (DL) reasoning services for OWL ontologies. It is used to check the consistency of the developed Construction Safety Ontology.

3. Based on the Construction Safety Ontology, SWRL rules are then developed to represent OSHA regulations. Also, the rule set can be customized and rules can be added by subject matter experts according to their specific requirements.

4. After connecting the ontology with *Tekla*, a commercial BIM software platform, individuals/instances of the safety concepts defined in the ontology are generated using BIM project information. Properties of each individual, such as geometry information, are obtained through BIM.

5. Facts including the knowledge base and individuals generated from BIM are passed to the Jess rule engine to be checked against SWRL rules defined earlier by a *Safety manager*.

6. Once new knowledge has been inferred by the rule-checking process, *Jess* updates the ontology.

7. The updated OWL ontology is then linked with the BIM platform to visualize inferred knowledge, such as required safety protective systems and protective safety zones.

8. Finally, project specific JHA along with a 4D building model are generated to support site level project safety planning and inspection.

5.5 Implementation and Results

5.5.1 SWRL rule development

A set of safety best practices from American Society of Concrete Contractors (ASCC) and American Concrete Institute (ACI) is interpreted into SWRL rules using the ontology's concepts.

The first rule set shows the requirements of setting up a protective zone during formwork stripping for CIP slab and CIP column. In terms of CIP slab, Rule-StrippingZone1 intends to compute the height of the stripping zone and its direction by referencing the slab element itself. The height of the stripping zone is set to be the same as the distance to the lower level from the slab. Similarly, Rule-StrippingZone2 computes the dimension of the stripping zone for stripping column based on the height

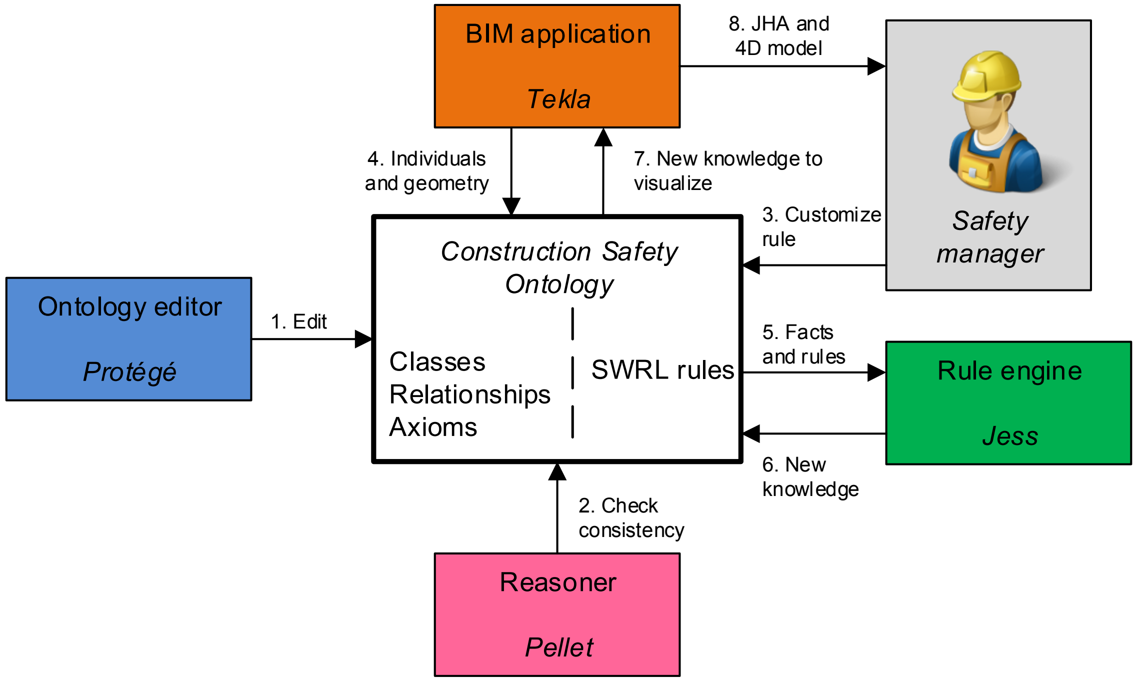


Figure 32: System architecture of ontology-based hazard identification application in BIM

of the column to represent the impact area once formwork fails. And the reference position of stripping zone to the slab/column is set to "below" and "around" to facilitate the visualization of the stripping zones in BIM later on. The second rule set shows the requirement for platforms and access for workers. It is recommended to use work platform to pour tall concrete columns to provide safe working area at heights. The height of the column can be customized to fit different requirement from different organizations. Four meter is used in this rule example. All units were converted from U.S. standard to metric in the SWRL rules.

Best Practice -1:

Barricade off the work area to be stripped. Only authorized personnel allowed in the stripping area.

(Stripping Forms Example JHA [9])

SWRL Rule -1:

Task_CIP_Slab(?tcs) $\bigwedge$ *consistOf(?tcs, ?ss)* $\bigwedge$ *Strip_Slab(?ss)* $\bigwedge$ *consistOf(?ss, ?bf)* $\bigwedge$ *Break_Forms_Loose(?bf)* $\bigwedge$ *needResources(?bf, ?sz)* $\bigwedge$ *Stripping_Zone(?sz)* $\bigwedge$ *produce(?tcs, ?cs)* $\bigwedge$ *CIP_Slab(?cs)* $\bigwedge$ *hasDistanceToLowerLevel(?cs, ?dis)* $\rightarrow$ *hasHeight(?sz, ?dis)* $\bigwedge$ *spaceReferencePosition(?sz, "below")*

(SWRL Rule-StrippingZone1)

Task_CIP_Column(?tcc) $\bigwedge$ *consistOf(?tcc, ?sc)* $\bigwedge$ *Strip_Column(?sc)* $\bigwedge$ *consistOf(?sc, ?bf)* $\bigwedge$ *Break_Forms_Loose(?bf)* $\bigwedge$ *needResources(?bf, ?sz)* $\bigwedge$ *Stripping_Zone(?sz)* $\bigwedge$ *produce(?tcc, ?cs)* $\bigwedge$ *CIP_Column(?cc)* $\bigwedge$ *hasHeight(?cc, ?h)* $\rightarrow$ *hasWidth(?sz, ?h)* $\bigwedge$ *spaceReferencePosition(?sz, "around")*

(SWRL Rule-StrippingZone2)

Best Practice -2:

Any high construction job requires a method of access and a work area or work platform.

(American Concrete Institute[55])

SWRL Rule -2:

CIP_Column(?cc) $\bigwedge$ *hasHeight(?cc, ?h)* $\bigwedge$ *Task_CIP_Column(?tcc)* $\bigwedge$ *produce(?tcc, ?cc)* $\bigwedge$ *consistOf(?tcc, ?pc)* $\bigwedge$ *Pour_Column(?pc)* $\bigwedge$ *consistOf(?pc, ?pgc)* $\bigwedge$ *Pouring_Columns(?pgc)* $\bigwedge$ *swrlb:greaterThan(?h, 4000.0)* $\rightarrow$ *needResources(?pgc, Platform)*

(SWRL Rule-Platform1)

5.5.2 Individual generation

The individual generation process is illustrated in Figure 33 as an example. Individuals are generated based on the information both from the safety ontology and BIM. In Figure 33, *CIP_Column_13785* is generated as an individual of CIP_Column. Related classes are also generated to the instance level as shown from the snippet of OWL RDF/XML of this individual in Figure 34 including activity, task, resource, potential hazard, etc. In addition, information such as geometry and schedule obtained from BIM are attached to the individual.

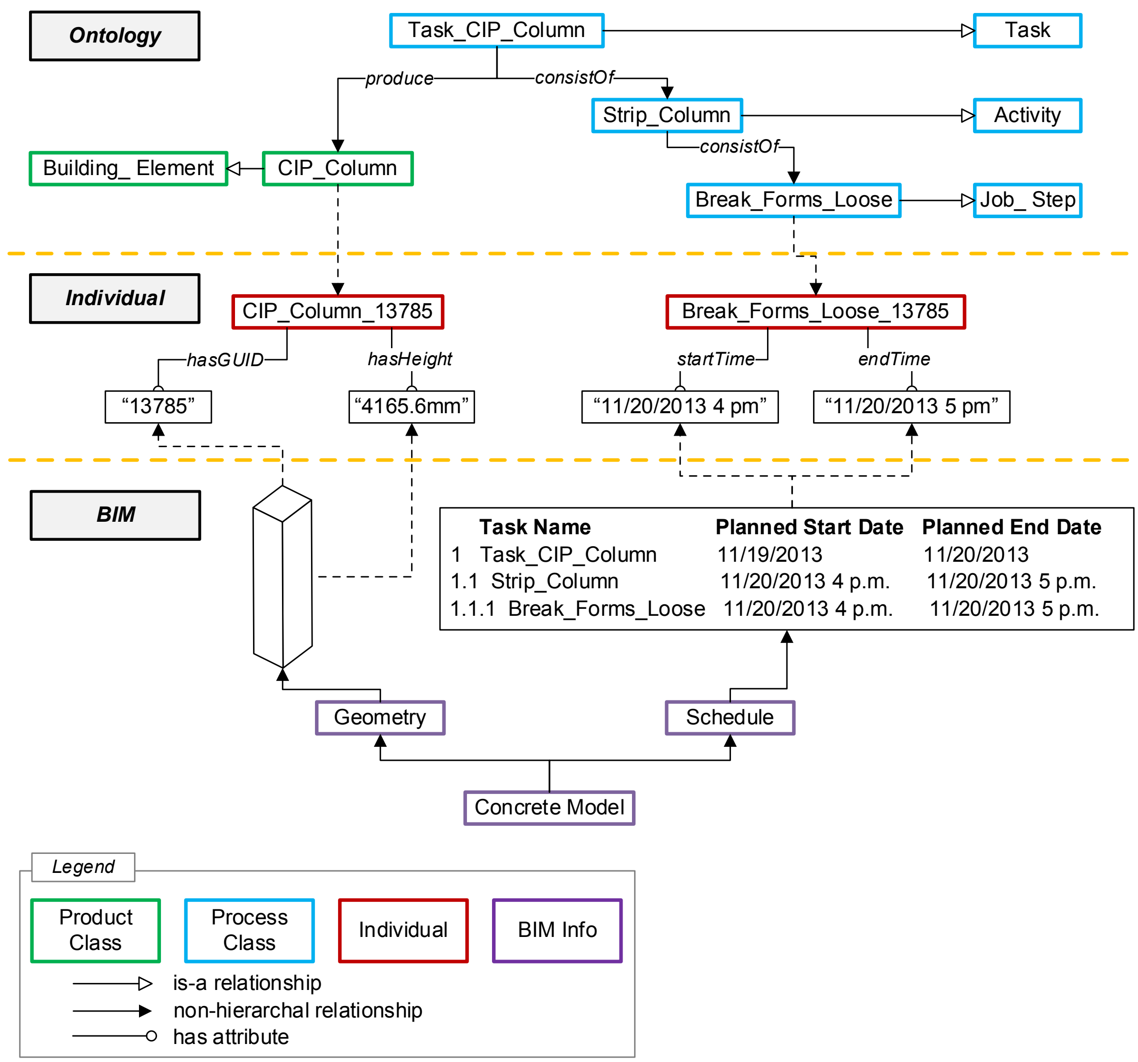


Figure 33: Individual generation based on both ontology and BIM

```
<Task_CIP_Column rdf:ID="Task_CIP_Column_13785">
  <consistOf>
    <Strip_Column rdf:ID="Strip_Column_13785">
      <consistOf>
        <Break_Forms_Loose rdf:ID="Break_Forms_Loose_13785">
          <hasHazards rdf:ID="Sprain_13785"/>
          <hasHazards rdf:ID="Unexpected_Form_Release_13785"/>
          <hasHazards rdf:ID="Strain_13785"/>
          <needResources rdf:ID="Concrete_Crew_13785"/>
          <needResources rdf:ID="Stripping_Zone_13785"/>
        </Break_Forms_Loose>
      </consistOf>
    </Strip_Column>
  </consistOf>
...
  <produce>
    <CIP_Column rdf:ID="CIP_Column_13785">
      <hasHeight rdf:datatype="http://www.w3.org/2001/XMLSchema#float"
      >4165.6</hasHeight>
      <hasGUID rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
      >13785</hasGUID>
    </CIP_Column>
  </produce>
</Task_CIP_Column>
```

Figure 34: Snippet of OWL RDF/XML showing an individual of Task_CIP_Column.

5.5.3 Individual update and visualization

In this example, dimensions of an inferred Stripping_Zone are computed by running the *Jess* rule engine (see Figures 35 and 36) and evaluating the SWRL rule. The BIM is updated to visualize the stripping zone when stripping the column.

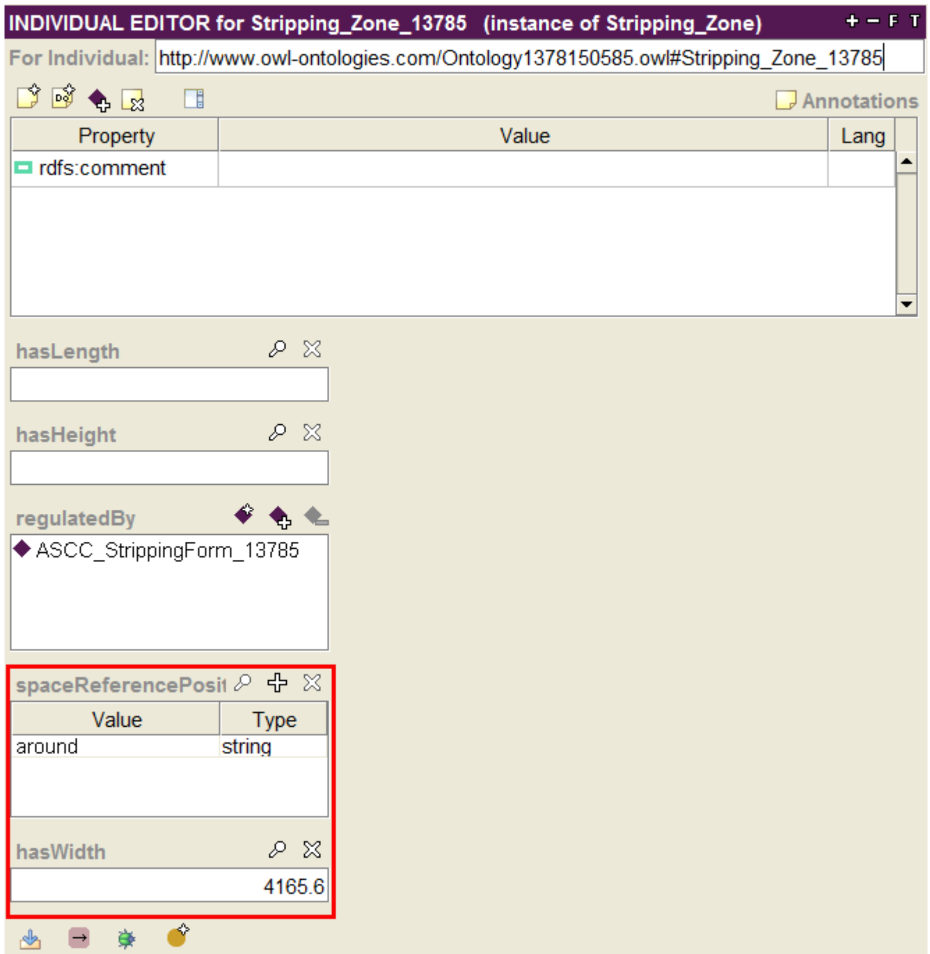


Figure 35: Computed dimensions of Stripping_Zone_13785 in Protege

```xml
<Stripping_Zone rdf:ID="Stripping_Zone_13785">
  <hasWorkSpaceDepth1 rdf:datatype="http://www.w3.org/2001/XMLSchema#
     float"
  >4165.6</hasWorkSpaceDepth1>
  <spaceReferencePosition rdf:datatype="http://www.w3.org/2001/
     XMLSchema#string"
  >around</spaceReferencePosition>
  <regulatedBy>
   <ASCC_StrippingForm rdf:ID="ASCC_StrippingForm_13785"/>
  </regulatedBy>
</Stripping_Zone>
```

Figure 36: Snippet of OWL RDF/XML showing an individual of Stripping_Zone

5.5.4 Automated JHA and reporting

A JHA prototype was developed using Microsoft Visual C# to implement the ontology-based hazard identification application (Figure 37). The JHA Advisor user interface is designed to leverage different sets of BIM and the Construction Safety Ontology. The general steps of applying the prototype are listed as follows:

1. Load construction schedule from the building model
2. Load Construction Safety Ontology as OWL format
3. Generate individuals based on both project schedule and ontology
4. Output individuals into new OWL file
5. Use *Jess* rule engine to check individuals and infer new knowledge

6. Re-load individuals from updated OWL file to visualize protective zones and to update schedule to include safety tasks

7. Review the construction sequence according to 4D model simulation

8. Generate the JHA report including the JHA results and also the snapshot of the simulated 3D building model

The concrete structural model of a real project in Atlanta, Georgia is shown in Figure 38. All building elements were linked to a corresponding construction schedule. Construction schedules in BIM typically do not show high levels of detail. For example, detailed activities, such as a column forming activity for every instance of a column, are often not listed in the Gantt chart. Instead, the schedule usually represents these through a summary activity, e.g. one activity that represents all column construction activities on a given level. The developed JHA program is capable of populating the detailed construction schedule depending on pre-allocated percentage of the time for each activity and job step. The time percentage used for each activity and job step is stored in the ontology as an attribute, which then will also be generated for each individual during the individual generation process. At the same time, relevant safety information is also retrieved. Such activity level based construction simulation is helpful to practitioners as it communicates where and when safety equipment is needed and needs to be removed. Thus, the developed user interface provides a valuable tool that may find popular application in the field as it increases communication among project stakeholders. The smallest time step for the purpose of the simulation was set to a minute in the developed program to allow for micro-level analysis of the activities.

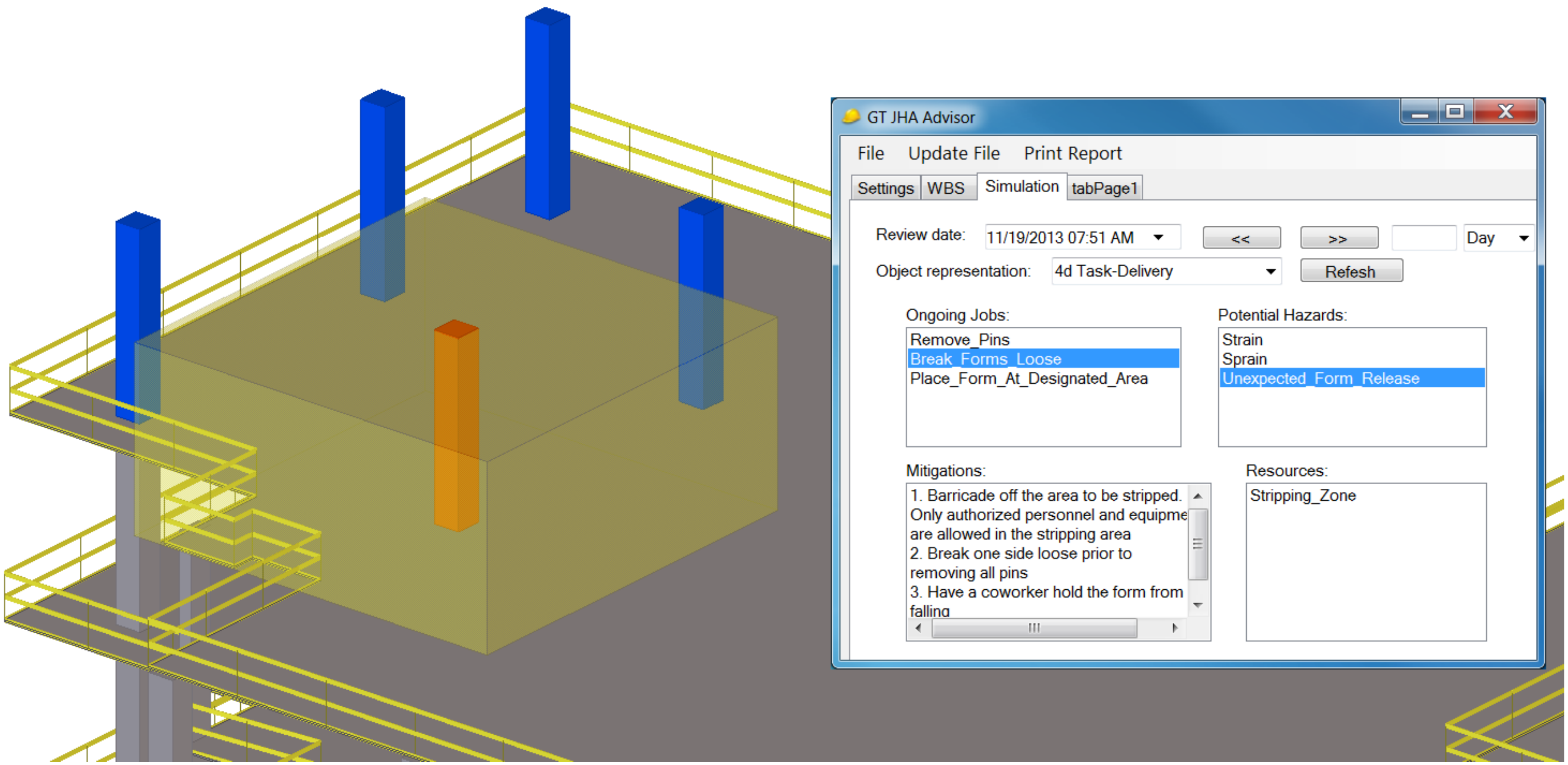


Figure 37: JHA Advisor Interface

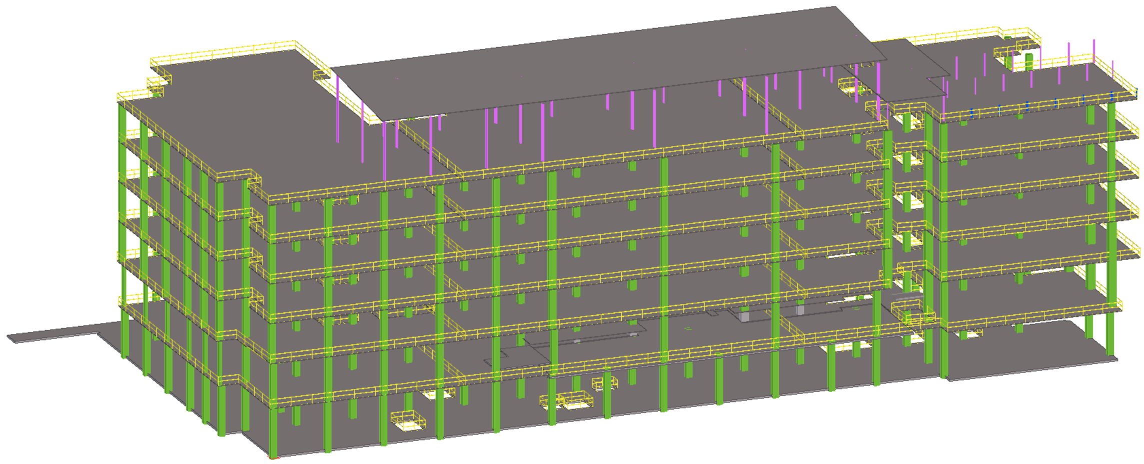


Figure 38: The concrete structural model in Tekla Structures

For each task in the schedule, the corresponding Activity, Job_Step, Potential_Hazard and Mitigation are shown (see Figure 37). An informative report (see Figure 39) was automatically generated by the system as an Excel sheet. As can be seen in this example, the JHA template of Table 6 is applied to the "Break_Forms_Loose" job step and its related safety resources, and supplemented with the view of the simulated BIM according to schedule. According to the review time of the 4D simulation of the project, the JHA related elements are shown in orange to be distinguished from other ongoing tasks that are shown in blue. Such JHA reports can not only provide safety analysis in a time-efficient manner, but it can also become a useful safety training tool for improving worker's safety awareness and their understanding of the surrounding working environment.

5.6 Discussions and Conclusions

5.6.1 Limitation and discussion

Initial implementation and test shows that the proposed approach can support a more comprehensive project safety management leveraging BIM technology. The identified main limitation is that the JHA knowledge would not be able to consider construction site layout issue since information such as terrain, site logistics, and construction equipment operation is currently not included and represented in BIM. Some examples include power line proximity issue, struck-by hazard led by heavy equipment operations, and cave-in hazard.

Job Hazard Analysis		
Project Name: GT_EBB	**Analyst:** Safety Manager A	**Date:** 11/18/2013 3:30:59 PM
Review Time: 1/14/2014 10:20:00 AM		
Task Name: Column	**Activity:** Strip_Column	
Job Step: Break_Forms_Loose		
Protential Hazard: Unexpected_Form_Release		
Recommended Procedures:		
	1. Barricade off the area to be stripped. Only authorized personnel and equipment are allowed in the stripping area	
	2. Make sure there is proper lighting	
	3. Have a coworker hold the form from falling	
	4. Clear all concrete and loose material from forms to prevent anything from falling overhead during stripping	
Resources:		
	Stripping_Zone	

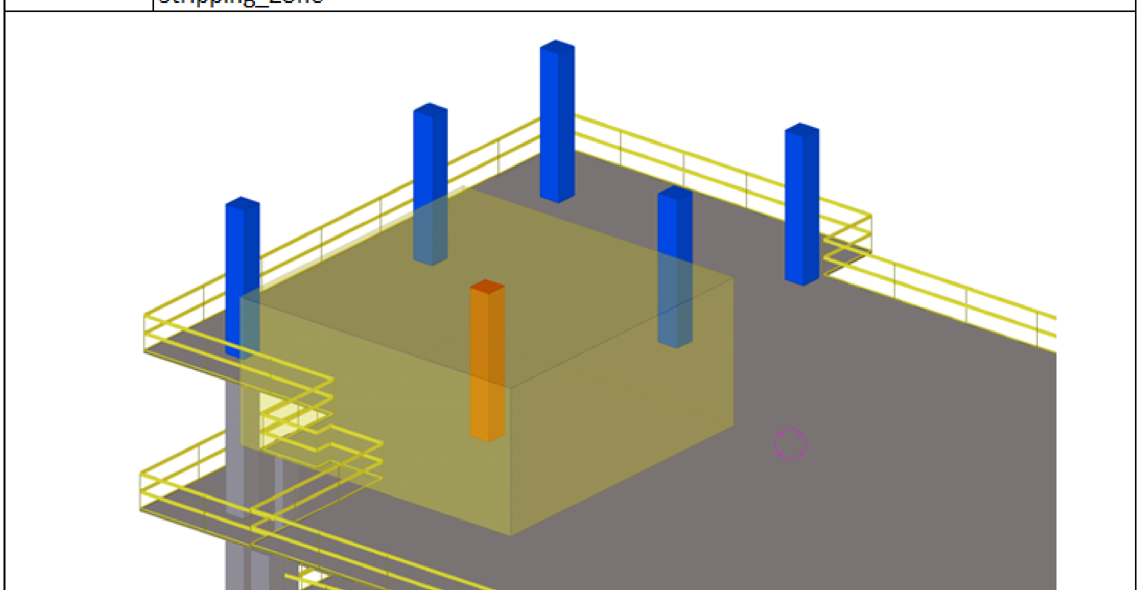


Figure 39: Sample JHA report generated by JHA Advisor automatically (Grey – Finished, Orange – Ongoing Task in Review, Blue – Other Ongoing Task)

5.6.2 Conclusions

Based on the developed framework, an automated ontology-based JHA in BIM prototype was developed. The prototype introduces significant automation in existing manual/experience-based JHA processes allowing a user to apply different sets of JHA on building information models. Simulation of safety and visualization of models with safety resources is the result. The developed knowledge or best practice can be transferred and applied by safety and field staff on construction sites. This may include individuals with limited safety knowledge and levels of safety experience. The prototype allows a safety engineer or manager to plan for safety at the front-end of a project automatically. It further assists in decision making that will be made by humans. In addition, the proposed JHA-BIM tool demonstrated other benefits. For example, when the schedule of a project changes, the user can re-run the system and quickly receive updated results of the hazard analysis.

CHAPTER VI

WORKSPACE COMPUTATION, VISUALIZATION, AND ANALYSIS

This chapter describes an approach that collect, formalize, and reuse historical activity-specific workspace information for automated activity-based workspace visualization and workspace congestion identification in BIM. It explains the process of data collection, workspace parameter computation, and its integration into Construction Safety Ontology.

6.1 Introduction

Traditional safety planning mainly relies on manual observation, which is labor-intensive, time-consuming, and thus highly inefficient. The link between planning for safety and work-task execution is often weak: for example, many contractors use two-dimensional drawings or field observations to determine hazard-prevention techniques [88, 115]. The resulting safety plans are often error-prone due to subjective judgments of decision makers. Currently, historical workspace information for an activity and the corresponding contextual information depicting the condition under which the activity is accomplished are not stored. Hence, workspace planning for work activities in construction planning is often overlooked. This leads to workspace congestion which may largely impede worker safety and productivity on a construction project. There is a need for an approach to collect, formalize, and reuse historical activity-specific workspace information.

This chapter describes an empirical study approach that collects the work activity specific workspace, obtains the workspace parameters, visualizes the workspace, and detects workspace conflicts in building information models. A BIM-based application prototype for workspace visualization is presented which shows how this approach can assist activity-level construction planning.

6.2 Background

6.2.1 Construction Workspace Representation

Representation and analysis of workspace for construction activities in 4D environments during the planning, scheduling, and eventually even at design phase is encouraged since it minimizes workspace congestion and conflicts which frequently happen at construction sites. It keeps also the workforce away from working more productively.

Thabet and Beliveau [103] and Riley and Sanvido [87] presented a scheduling model that incorporates work space constraints in the scheduling of repetitive work in multistory buildings. Their model proposes a method to define and quantify work space parameters (space demand <physical space demand and surrounding space demand >and space availability). Akbaş [3] described a geometry-based modeling and simulation approach called GPM for modeling and simulation of construction processes based on geometric models and techniques, which provides improved modeling and simulation techniques for construction operations and more effective use of geometry for construction practice and research. However, GPM relies on the user to define the crew parameters and sequences to generate the activities and simulate the process given these parameters.

Akinci et al. [5] firstly developed space templates linked to construction method templates to enable users to define the space requirements of different construction methods; secondly, developed the prototype system, the 4D WorkPlanner Space Generator (4D SpaceGen) [4], that uses the spatial requirement knowledge captured generically in the space templates to automatically generate the project-specific instances of spaces; thirdly, formalized time-space conflict analysis as a classification task and addressed these challenges by automatically (1) detecting space conflicts, (2) categorizing the conflicts, and (3) prioritizing the multiple types of conflicts between conflicting activities [6]. However, the material travel path is not considered as well as the definition of required workspace. Choi et al. [25] classified workspace by its function and its relocatability to further represent different characteristics of a workspace, which enables better integration of the workspace requirement and their planning processes. One limitation is that enormous efforts are required to prepare the input data such as detailed construction schedules.

Mallasi, Z. and N. Dawood [67] applied entity-based 4D CAD technology for detecting workspace congestion to help identify potential safety hazards on-site using critical space-time analysis (CSA) in 4D visualization. The proposed CSA associates certain visual features for workspace planning with the workspace competition. The PECASO (Patterns Execution and Critical Analysis of Site-space Organization) prototype was developed to encapsulate and evaluate the outcome of the CSA. M.E. Haque and M. Rahman [50] linked a 3D BIM model with schedule and construction space requirement, and simulated the 4D model to detect whether there is any space conflict during the activities. Jongeling et al. [56] used distance between different types of work as an important factor in safe and productive work execution by manually extracting 4D spatial content from 4D CAD models. However, no scientific method is provided for generating space requirement.

Many existing studies focused on critical space analysis and space planning which use workspace as an input in their system. However, neither of these approaches can provide reliable spatial information since their workspace input are either estimated based on authors' experience or it requires the user to define their own input. Riley and Sanvido [86] concluded that different materials and activities have repeating (predictable) space needs from one project to the next. The challenge is to find more appropriate ways to represent workspace and to suggest acceptable workspace parameters.

6.2.2 Location-Tracking in Construction

Safety risks on construction sites are often closely related to the proximity of construction materials, equipment, and workers to nearby hazards. Some of these are explicit, for example, the risk of falling from the leading edge of a concrete slab floor. Some of the risks have also been defined and quantified in Hallowell & Gambatese [47] and Rozenfeld et al. [89]. Some researchers recommended using positioning devices to locate construction resources and deliver pro-active safety information in real-time to mitigate a worker from entering a hazardous area [98, 80]. Maalek and Sadeghpour [65] studied the performance of an Ultra Wideband (UWB) tracking system in static mode under conditions that commonly occur on construction sites. They proved that the accuracy of commercially-available real-time location tracking technology can be used to display resource location in information models. They further indicated that "the accuracy of the system could be used in the definition of the size of buffer zones in construction site safety applications". Many technologies exist today that might offer a solution to real-time hazard detection and warning pro-actively based on pre-defined and geo-referenced hazard zones. Example research using technology as it relates to construction safety is small GPS data loggers [84] and UWB [23]. Although each technology has shortcomings, both of them can gather valuable activity-based location data from worker and equipment movements. Once data is processed, information has the potential to support workspace modeling and visualization.

A construction site is a very dynamic environment in which workspace related to construction activities changes continuously. The locations and volumes of these spaces change in three dimensions and over time, according to project-specific design data. Unless advanced automation or lean approaches are applied, congestion among various work activities can often not be eliminated, which can lead to additional safety hazards [69]. Hence, there is a need for more effective activity-level construction safety planning.

6.3 Objective and Scope

This research aims to develop a general approach that collects, formalizes, and reuses historical activity-specific workspace information for automated activity-based workspace visualization and congestion identification in BIM. To limit the scope, this study focuses on concrete column construction activities due to their high risk of hazards and severity of potential incidents and injuries. According to the report of the Bureau of Labor Statistics (BLS) [105], poured concrete foundation and structure contractor has been recognized as one of the most high-risk specialty trades. The GPS devices used in this research are commercially available Wintec G-Ray 2 data logger (see Figure 40). The error analysis of this device can be found in Pradhananga and Teizer [84].

Figure 40: Example of a GPS data logger (Wintec G-Rays 2)

According to OSHA, "*Routes for the suspended loads should be pre-planned in order to ensure that no worker has to work directly below a suspended load (except for those workers who must hook up or unhook the load, or work on the initial connection of the steel members).*" From 1992 to 2006, 307 crane accidents in the private construction industry sector caused the death of 323 workers [29]. In 2006, cranes contributed both as primary and secondary source of injuries to 72 of the fatal occupational injuries in the United States. This number is slightly lower than the average number of 78 fatalities per year between 2003 and 2005. 61% of these fatalities were categorized as "contact with objects or equipment" [104]. In 2012, ENR published results to a case study stating that 'worker contact' was the cause of accidents in 46.7% of over 700 investigated crane-related accidents. As many of these statistics indicate, safe crane operation requires well-coordinated activity planning including all related processes and resources, such as involving the workers that rig material and the equipment [48]. In view of these statistics, detecting struck-by falling objects hazard is the focus in this research.

6.4 Workspace Modeling and Visualization

The goal and intention is to develop an activity-based workspace modeling method, and to create a framework to integrate activity-based workspace with BIM. The workspace sets considered in this study include:

1. Building component space: the space building component itself occupies, typically it is shown in BIM as a final product;

2. Worker space: the required space for a crew to perform work;

3. Space for material handling path: the handling path required for material movement, for example, the space required for moving rebar cage from its staging area to the installation location using crane.

4. Equipment space/temporary structure space: the space occupied by equipment such as crane and scaffolding.

5. Protective space: the space needed to protect worker from safety hazards such as a post-tensioning zone during tensioning operations.

Conflict between two different workspace results in different consequence. Table 7 shows the workspace conflict taxonomy:

1. Design clash caused by two building components is outside the scope of this research since existing commercial available applications can solve this issue.

2. Congestion can be caused by several reasons, for example, worker space clashing with building component space makes less space available for workers. The workspace congestion usually results in disruption in workflow, which often leads to lower productivity [56].

3. Safety hazard can be caused by the conflict of either protective space and worker space or protective space and space for material handling path. It needs to be noted that safety hazard posted by the activity itself has been considered in previous JHA analysis in the last chapter. Table 8 shows examples for two types of space interference, which can lead to safety hazard.

Table 7: Workspace conflict taxonomy

(adopted and modified from [6])

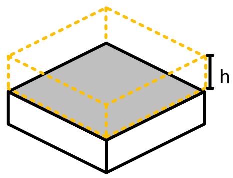
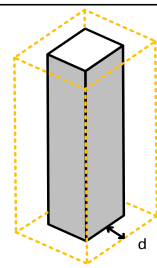
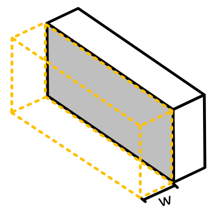
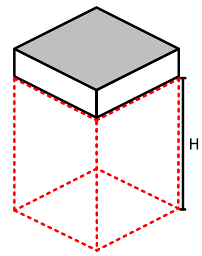
		Activity 1				
		Building Component	Worker Space	Material Handling Path	Equipment Space	Protective Space
Activity 2	Building Component	Design Clash	Congestion	Congestion	Congestion	No Impact
	Worker Space		Congestion	Congestion	Congestion	Safety Hazard
	Material Handling Path			Congestion	Congestion	Safety Hazard
	Equipment Space				Congestion	No Impact
	Protective Space					No Impact

Table 8: Examples of each space conflict leads to safety hazard

Type of space interference	Example
Protective space × Worker space	Worker works under overhead loads (e.g. rebar cage, formwork, concrete bucket, precast concrete elements)
Protective space × Material handing path	Unauthorized worker move material through post-tensioning area during tensioning operations

In this study, workspace is generated corresponding to the reference object (see Table 9). Reference surfaces are illustrated in grey color, required workspace for workers is shown with yellow dashed lines, and protective space is shown using red dashed lines.

Table 9: Workspace representations

Reference position	Above	Around	In front of	Below
Diagram				
Example	Worker space for pouring concrete slab	Worker space for rebar work on column	Worker space for setting pins for wall formwork	Protective space preventing falling object hazards below crane load
Parameter	h: worker height	d: depth of worker space	w: width of worker space	H: distance between load and ground

6.5 Implementation and Results

It is assumed that worker location data can provide approximate workspace that was used to complete a work task. The data then generate the workspace parameters for a type of work activity. An occupancy grid model is used for calculating the frequency of the visits of a worker to a predefined virtual cube which represents part of the work area. After creating the occupancy grid map following Cheng et al. [23], algorithms were developed for generating and retrieving workspace parameters based on data densities. Then, these parameters were used to represent distance offsets with reference to a building object. Finally, the parameters are used to generate the required workspace for each activity in BIM. Then it will allow for safer work activity planning, if the same construction activity and method are used.

6.5.1 Description of the experimental setting

A three-day experiment was conducted on a construction site, which is a multistory concrete structure (See Figure 41). Data were collected on concrete column construction activities on the fifth floor, and included 1) frame column formwork, 2) column formwork bracing, 3) pour column concrete, and 4) strip column formwork. Two GPS tags were tagged to each of the hardhats of three volunteering workers who were involved in the activity (See Figure 42). A tower crane was involved in lifting and moving formwork and concrete bucket. A video camera was set up at a nearby structure to record the progress of the experiment. The video data helped in analyzing the GPS data after data collection.

Figure 41: The construction site for conducting experiments

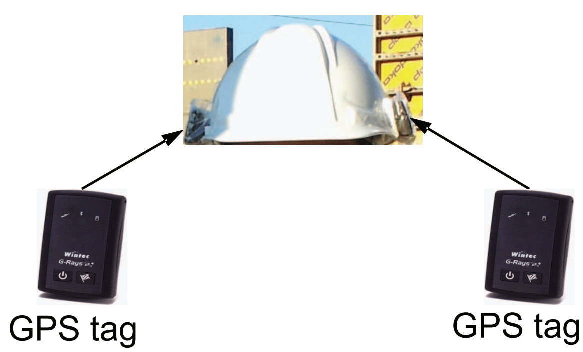


Figure 42: GPS data loggers mounted on subjects' hardhats

In addition, the accurate geometric information of the experimental environment of the complete structure was acquired using photogrammetry-based Unmanned Aerial Vehicle (UAV) [93] (See Figure 43). The collected 3D point cloud data were also used to establish correspondence between the GPS data and the location of the structure. Based on 51 pictures taken by the UAV (see Figure 44 as an example), a merged plan view of the construction site is generated as shown in Figure 45.

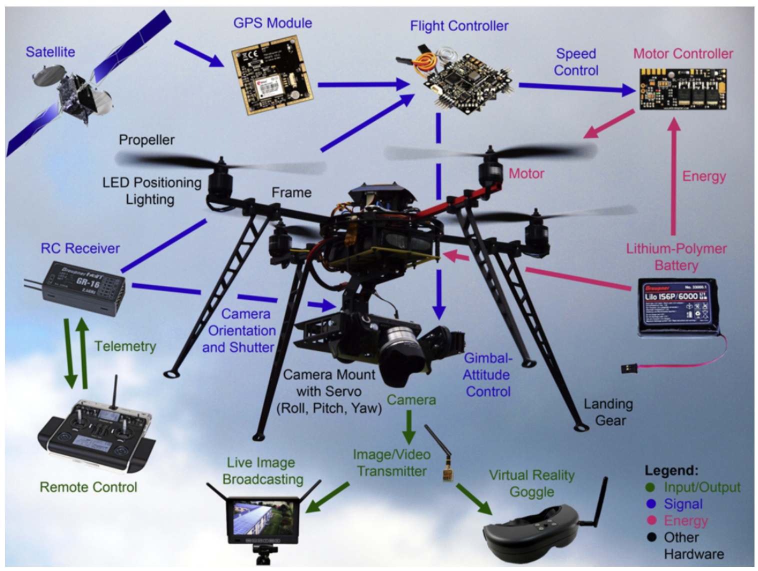


Figure 43: The main components of the UAV system [93].

6.5.2 Data processing

GPS data were first transformed from the world coordinate system to the local coordinate system of the building model. Since the average distance between columns is 6.4 m, the value 6.4 m was used as a threshold to remove GPS data outliers. The data were then filtered using a Robust Kalman Filter [33]. Kalman filtering, as it has been historically used for filtering and smoothing positioning or signal data, helped remove outlier data and error reads from the same type of GPS logger [84].

Figure 44: Picture from UAV at a way-point.

6.5.3 Workspace parameter computation

A 2D occupancy grid model is applied to visualize different worker activity levels. Based on the site dimension and accuracy of the GPS device, the construction space is divided into virtual square of identical dimensions: $0.5 \times 0.5\ m$. Figure 46 shows a grid-based map in plan view for installing formwork on one of the columns. The distribution of the required workspace and different activity levels are further explained using three different occupancy levels. Starting from the average point (illustrated using a yellow dot in Figure 46), areas that were occupied by the workers in 50%, 75%, and 100% of the time (it took them to install the formwork) are computed respectively following the spiral pattern (see Figure 47). These space sets are denoted as S^{50}, S^{75}, and S^{100}. Hence, three activity levels are marked with red, green, and blue bounding boxes in the occupancy grid map. The position of the column is shown

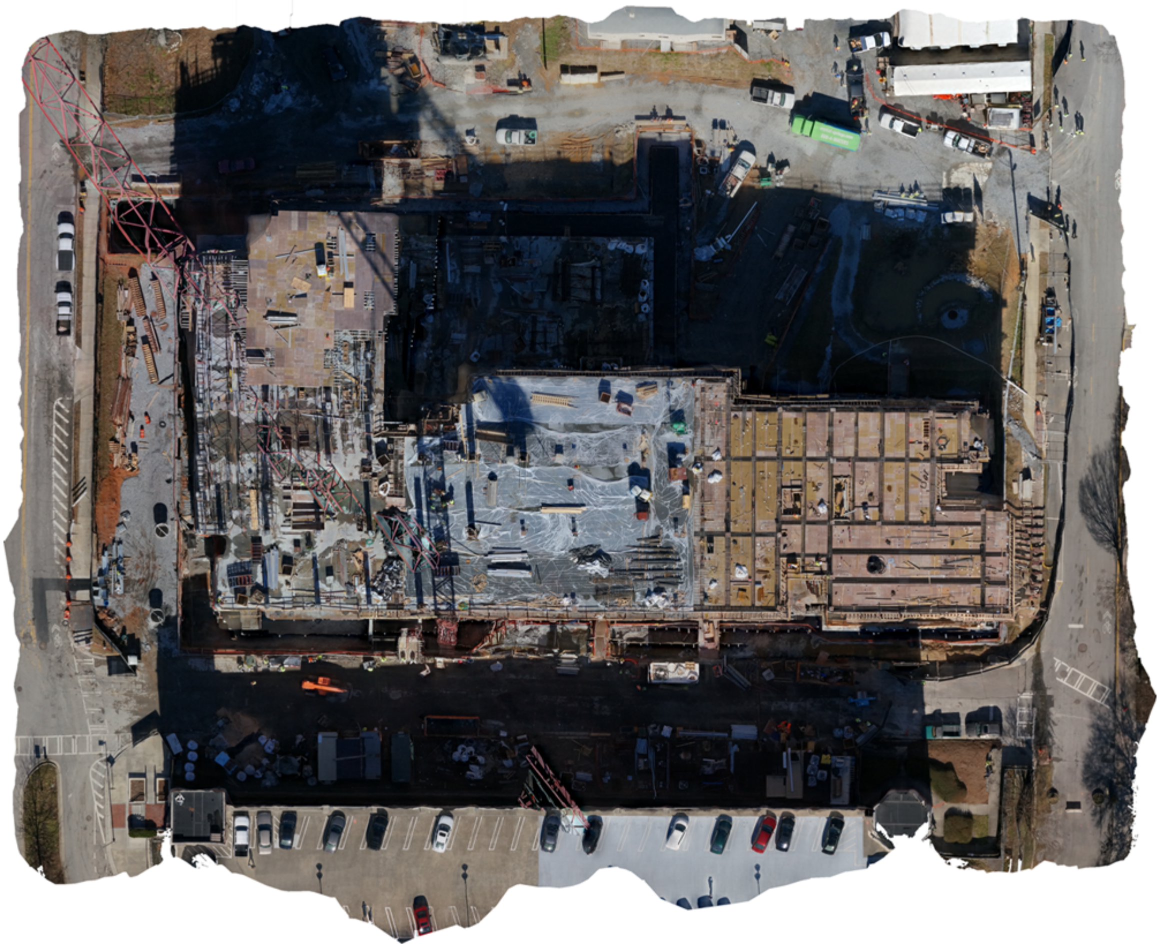


Figure 45: Plan view of the construction site generated based on 51 pictures taken by UAV.

as a small white rectangular box. Based on the collected data from all of the columns (see Table 10), the average workspace parameters for each activity are computed for 50%, 75%, 100% of all time spent in the work zone respectively. In Table 10, column # means the number of column from collected data sets. For each of the activity, mean value, median, and standard deviation (SD) are calculated. The mean value is used as the workspace parameter.

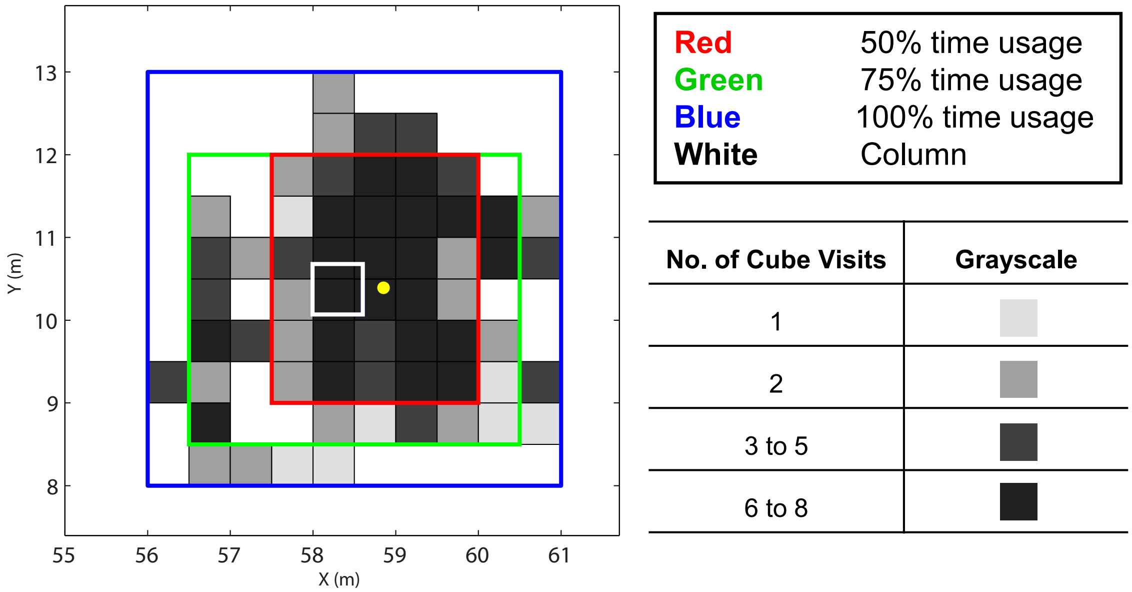


Figure 46: Occupancy grid model.

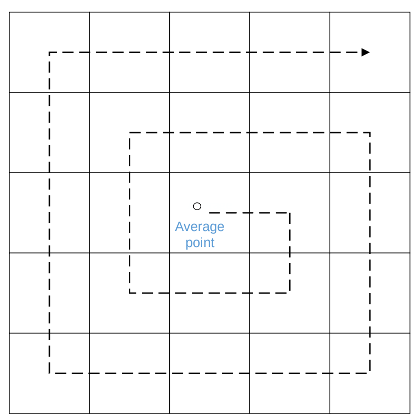
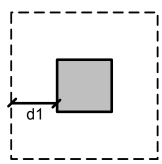
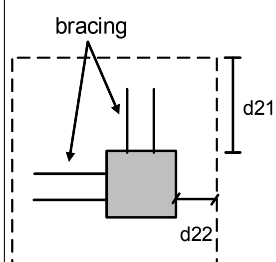
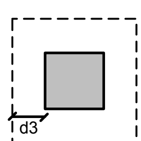
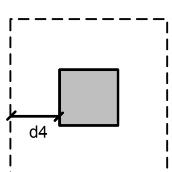


Figure 47: Spiral pattern for calculating three activity levels in occupancy grid map.

It is also observed that the location of the column with regards to its floor slab affects the spatial relationship between the column and its workspace. Since workers intend to stay away from the slab edge to avoid fall hazard (see Figure 48), the center of the workspace usually shifts away from the slab edge when the column is close to the slab edge or corner. In order to quantify the influence of the location of the column, another space parameter center shift denoted s is introduced. For each of the column, if one or two faces of the column are close to the slab edge, the distance between the workspace center and the column center is computed. As shown in Table 10, center shifts are calculated based on the average value of all these columns for activities: frame column, pour column, and strip column. Since the direction of column bracing depends on the location of the column and available space, center shift is not applicable.

Table 10: Workspace parameters for column construction activities (Unit: meter)

Activity	Diagram	Parameter	Column #	Time %	Mean	Median	SD	Center shift
Frame column		d_1	18	50%	1.23	1.3	0.19	0.42
				75%	1.69	1.7	0.15	
				100%	2.45	2.45	0.31	
				Time %	**Mean**	**Median**	**SD**	**Center shift**
Column bracing		d_{21}	18	50%	2.72	2.65	0.77	--
				75%	3.23	3.07	0.65	
				100%	3.92	4.04	0.65	
				Time %	**Mean**	**Median**	**SD**	
		d_{22}	18	50%	0.39	0.32	0.52	
				75%	0.53	0.5	0.36	
				100%	1.01	0.94	0.54	
				Time %	**Mean**	**Median**	**SD**	**Center shift**
Pour column		d_3	19	50%	1.04	0.95	0.17	0.2
				75%	1.37	1.32	0.21	
				100%	1.89	1.95	0.26	
				Time %	**Mean**	**Median**	**SD**	**Center shift**
Strip column		d_4	16	50%	1.16	1.11	0.26	0.67
				75%	1.59	1.54	0.29	
				100%	2.22	2.13	0.49	

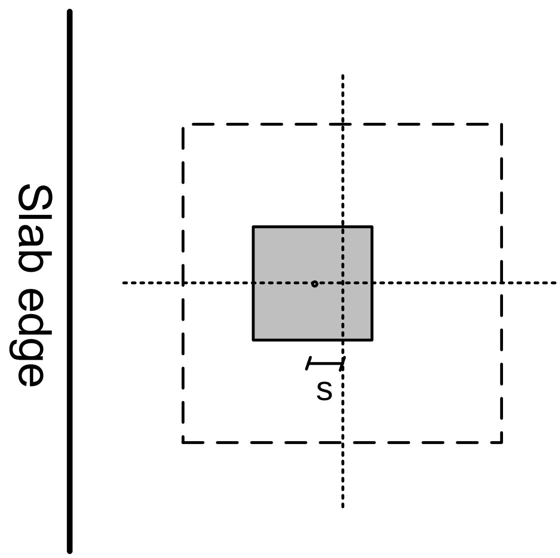


Figure 48: Workspace center shift.

During the data processing, the time used by each activity is also calculated (see Table 11). Even though productivity is not the focus of this study, it is used to automatically populate the start and end time of each activity in the next step for 4D simulation in BIM. Considering the break between the execution of each activity, time intervals are added (see Table 12). Also, as in reality the concrete crew will start to build new columns after they strip the column built the day before, the program caculates the time accordingly.

Table 11: Time use for each activity

Activity	Place_Rebar_Cage	Frame_Column	Column_Bracing	Pour_Column	Strip_Column	**Sum**
Time	17%	19%	18%	35%	11%	**100%**

Table 12: Time use for each activity with time interval

Activity	Place_ Rebar_Cage	*Time Interval*	Frame_ Column	*Time Interval*	Column_ Bracing	*Time Interval*	Pour_ Column	Strip_ Column	*Time Interval*	**Sum**
Time	13.6%	*4%*	15.2%	*8%*	14.4%	*4%*	28%	8.8%	*4%*	**100%**

6.5.4 Construction Safety Ontology extension with workspace parameters

Figure 49 shows an extension of Construction Safety Ontology with workspace information included (following the same legend in Figure 6). Each *Job_Step* is linked with a set of workspace including worker space, equipment space and etc. As an example, *Stand_Forms_Into_Place* (see Figure 50) needs concrete crew as a resource, which occupies *StandForms_WorkerSpace*. The computed workspace parameters are stored in workspace class as properties. In addition, the reference position of the workspace to building element is also specified according to Table 9.

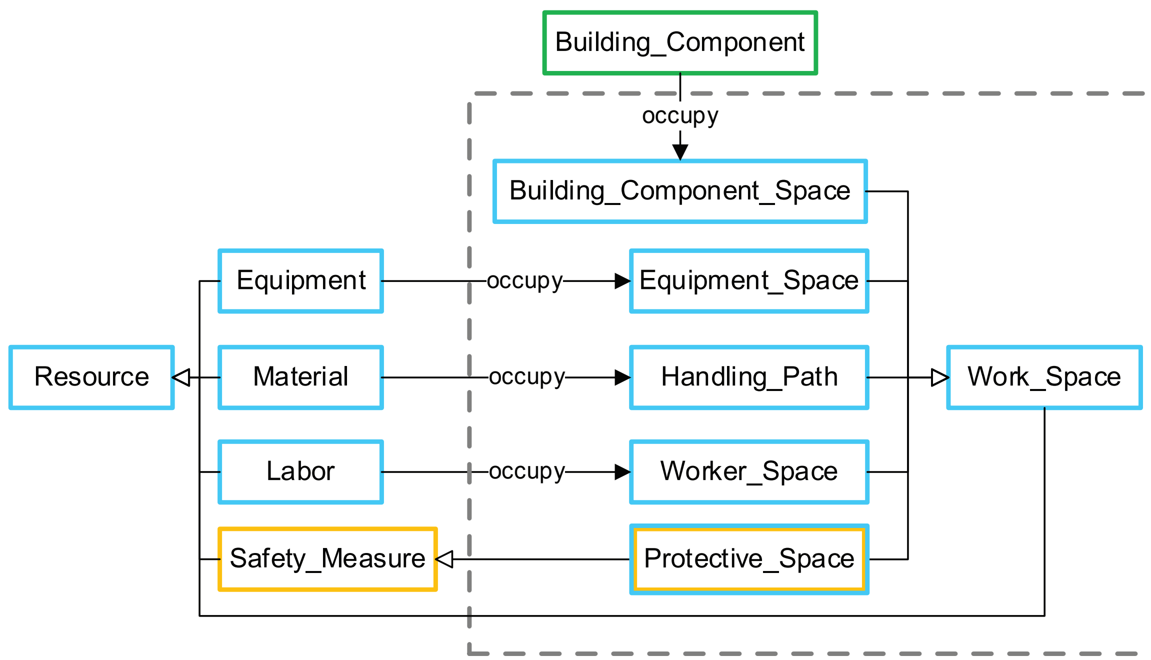


Figure 49: Extended Construction Safety Ontology to include workspace information

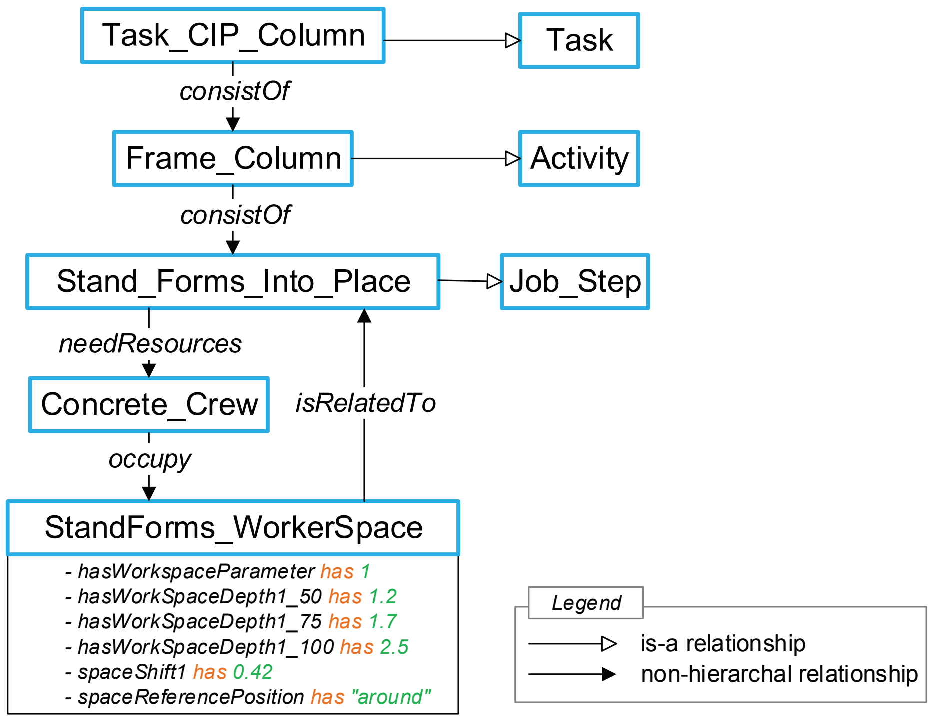


Figure 50: Workspace parameters for Stand_Forms_Into_Place (Job_Step)

6.5.5 BIM-based workspace visualization

Based on the master schedule made in the Task Manager in Tekla Structures, the detailed activity-level schedule needs to be populated for generating detailed workspace information. Instead of building one column after another, it is found that workers tend to work on activity after activity in reality, i.e. place rebar cage for all 8 columns and then install all of the 8 formwork. The pseudo-code for generating detailed schedule for each activity is shown in Algorithm 1 :

Algorithm 1 Pseudocode for detailed schedule calculation for each activity

```
for every day n do
    for every task m do
        a = getActivity(0, m)
        p = getTimePercentage(a) //get time percentage for a from ontology
        for every individual i do
            b = getActivity(i, m)
            calculateStartAndEndTime(b)
        end for
    end for
end for
```

Figure 51 shows the feasibility of generating and visualizing the activity-based workspace in BIM. Along with 4D simulation of the construction progress, at each time stamp, workspace sets can be visualized by referencing the building elements in BIM that are under construction. As shown in Figure 51, the workspace used for installing formwork for one concrete column (in orange) is illustrated using pink (50%), green (75%), and light blue (100%) cubes. The height of the space cubes is set to be equal to the height of the column as default. The percentage indicates the spatio-temporal relationship of occupied workspace and time required for the construction workers to complete the work task. The location of the column in regards to the slab is also computed to determine whether space center shift is needed. In Figure 51, since the column is close to the corner of the slab, the workspace sets are automatically shifted according to the center shift s from ontology. JHA also considers geometric condition of the column and insert *Fall_To_Lower_Level* potential hazard as shown in Figure 52.

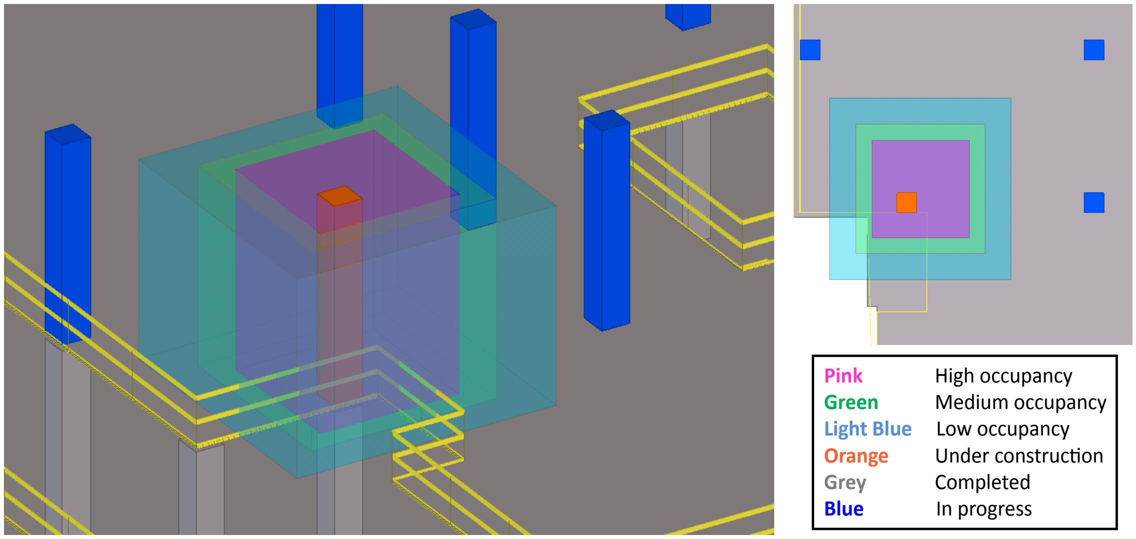


Figure 51: Workspace set visualization for frame column activity in BIM (Left: 3D view, Right: Top plan view)

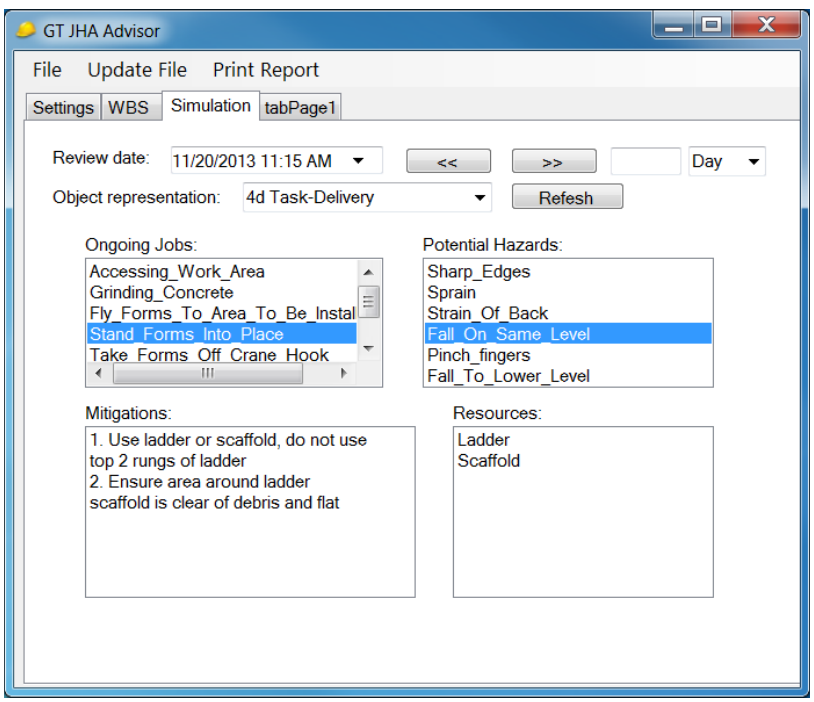


Figure 52: Job hazard analysis considering geometric condition

Since there are five different types of workspace for each activity as discussed in 6.4, it is necessary to specify what space types needs to be visualized. Given that this research mainly focuses on detecting potential safety hazard, only worker space and protective space are visualized.

6.6 BIM-Based Workspace Conflict Detection

Workspace conflicts are detected based on geometric conditions of different sets of workspace. According to Table 7, this research intends to mainly detect two types of major workspace conflicts: 1) congestion and 2) safety hazard. In terms of congestion, the space congestion degree can be determined for each of the activity based on their conflict volume, it is defined after the *ConflictRatio* in [6] and *Space Capacity Factor* in [103]. In terms of worker space, the space congestion degree further considers different occupancy levels of the worker space. It is considered that the cases of S_b conflicting with S_a^{100}, S_a^{75}, and S_a^{50} to be minor, moderate, and severe degree of congestion respectively. Safety hazards are detected once protective space conflicts with worker space or protective space conflicts with material handling space.

Based on Table 7, SWRL rules were developed to check against different conflict impact between each two workspace sets. The SWRL rules for the conflict between two worker space and the conflict between worker space and protective space are shown as below:

Worker_Space(?ws1) $\bigwedge$ *Worker_Space(?ws2)* $\bigwedge$ *conflictWith(?ws1, ?ws2)* $\rightarrow$ *hasConflictResult(?ws1, "congestion")* $\bigwedge$ *hasConflictResult(?ws2, "congestion")*

(SWRL Rule-SpaceConflict-WW)

Worker_Space(?ws1) $\bigwedge$ *Protective_Space(?ps2)* $\bigwedge$ *conflictWith(?ws1, ?ps2)* $\rightarrow$ *hasConflictResult(?ws1, "safety hazard")* $\bigwedge$ *hasConflictResult(?ps2, "safety hazard")*

(SWRL Rule-SpaceConflict-WP)

Note: A complete list of SWRL rules can be found in Appendix B.

6.6.1 Case study

1. Congestion detection:

   One of the most frequent workspace congestion observed at the construction site occurs between shoring construction and column construction when the project is facing tight schedule. For testing purpose, a compressed schedule was created so that shoring activity for the upper level slab and stripping column activity need to be executed at the same time. As shown in Figure 53, the space conflict is detected, and the user-interface of the prototype also displays the type and severity of the conflict. The space conflict detection uses the same approach as the clash detection in BIM.

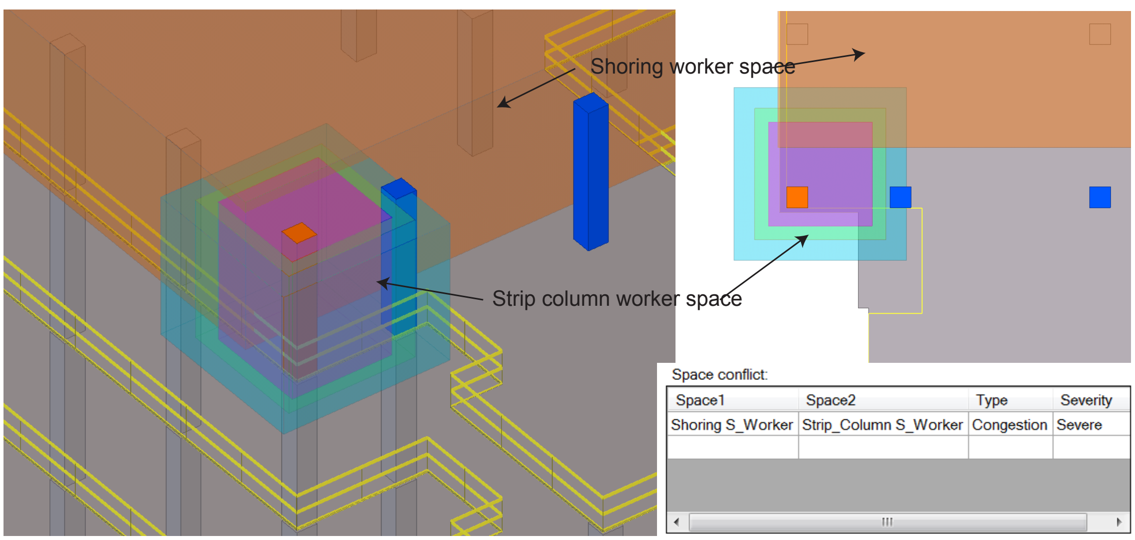


Figure 53: Workspace congestion identified between shoring and stripping column activity in BIM (Left: 3D view, Right: Top plan view)

2. Safety hazard detection:

   The safety hazard focused in the case study is the struck-by hazard caused by the overhead crane load. The prototype aims to detect space conflict between worker space and protective space underneath the crane load (crane lifting path). Crane lifting path is simplified using a rectangle with four meter width from material layout area to the location of the construction activity. Based on Table 9, protective space can be represented as a box-shape space between crane lifting path and the top level slab. Figure 54 illustrates the identified potential struck-by hazard caused by overlapping between crane lifting path and shoring worker space.

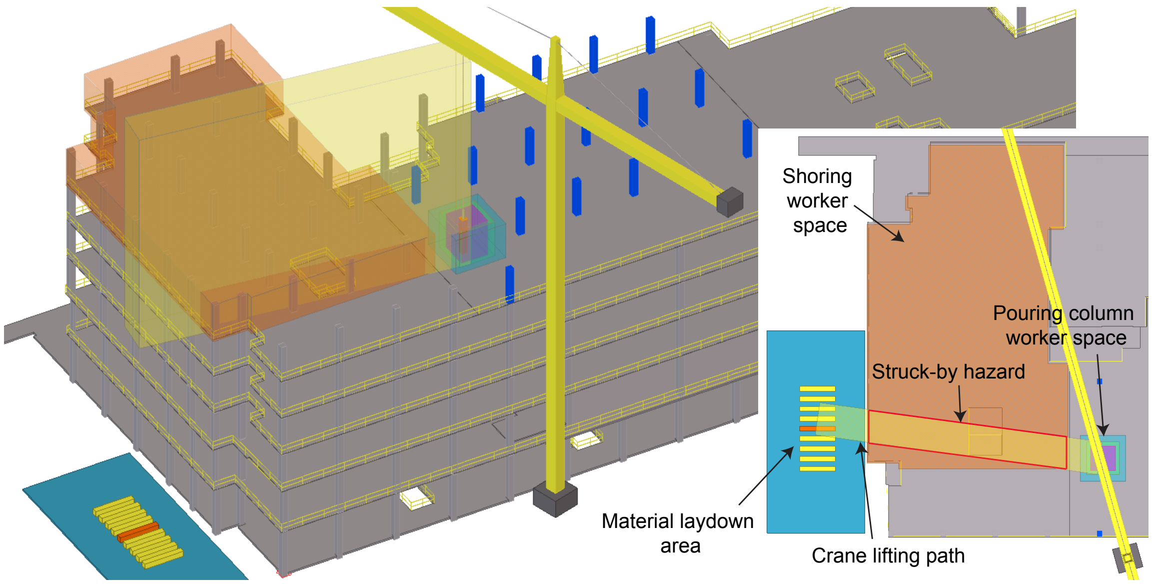


Figure 54: Struck-by hazard identified between crane lifting path for pouring column activity and shoring worker space in BIM (Left: 3D view, Right: Top plan view)

3. Finding safer construction sequence:

   One application of the developed prototype is to compare two construction sequences in terms of their safety levels. Two sequences were made for the construction project, one starts from section A to B and C, while the other one starts from section C to B and A. These two sequences have the same time duration which ensures the same productivity level. 4D simulations were run to identify potential struck-by hazards. The results were used to compare the level of safety, which assists the safety manager to select a safer sequence. 4D simulations were run with 5-minute interval for both construction sequences. Since the material layout area is located next to Section A, 25 potential struck-by hazards embedded with sequence 'ABC' were detected while zero potential struck-by hazard is detected from sequence 'CBA'. Figure 55 shows a series of comparison between these two sequences. Objects in blue are in progress, objects in orange are under construction, space in semi-transparent orange represents shoring worker space, space in semi-transparent yellow represents protective space for crane lifting path, and space set in semi-transparent pink-green-blue color is worker space for column construction activity.

6.7 *Discussions and Conclusions*

6.7.1 Discussion and future research

Future research will extend the current method and explore the opportunities 1) to use highly accurate GPS technology for location tracking, 2) to collect location tracking data from various work activities and projects in order to explore more accurate workspace representations for better workspace shape illustration, 3) to integrate workspace parameter into site layout planning or schedule optimization [91] for generating safer site layout and schedule, and 4) to conduct field trials that explore its application to traditional construction safety risk analysis.

6.7.2 Conclusions

This chapter describes an approach that collect, formalize, and reuse historical activity-specific workspace information for automated activity-based workspace visualization and congestion identification in BIM. GPS worker tracking data were collected to compute workspace parameters based on different occupancy levels for each work activity, which shows the feasibility of computing workspace parameters from location

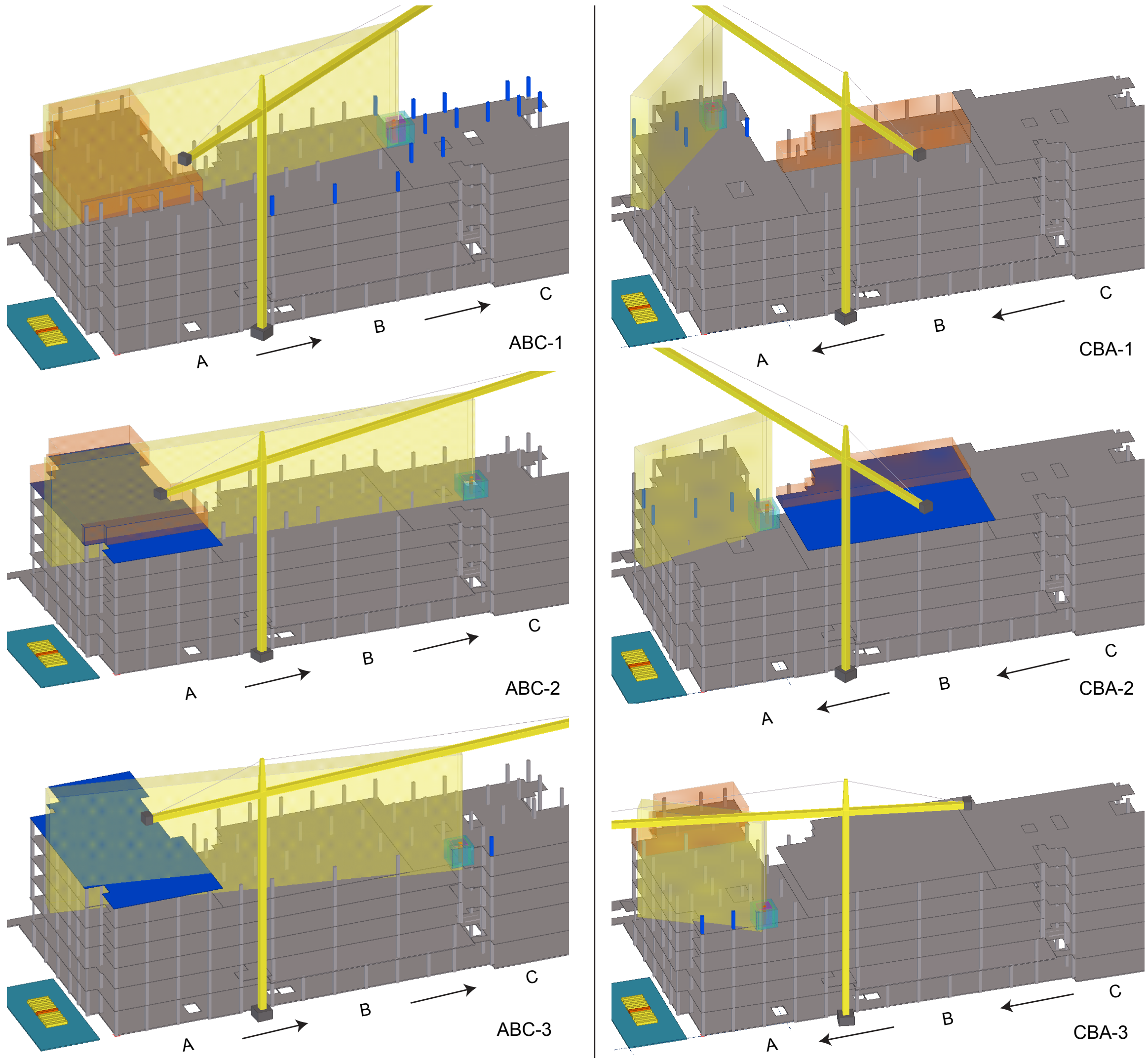


Figure 55: 4D simulation comparison between sequence 'ABC' and sequence 'CBA'

tracking data. The integration of generated workspace parameters and Construction Safety Ontology is explained for workspace visualization in BIM. Two types of workspace conflict: congestion and safety hazard, were successfully detected. The developed prototype shows the capability to visualize acitivity-based space sets, detect space conflict, and infer conflict consequence and severity. It also shows its application to compare two construction sequences to support safer scheduling decision-making.

CHAPTER VII

INTEGRATING AUTOMATED HAZARD IDENTIFICATION AND PREVENTION INTO PROJECT WORKFLOW

This chapter explains the integration of construction safety design, planning, and operation with project workflow. Use cases applying automated hazard identification and prevention are defined. Also, a review and comparsion on BIM platforms for supporting construction safety planning is discussed.

7.1 Process Map for Construction Safety Design, Planning, and Operation

A use case defines an exchange scenario between two well-defined roles for a specific purpose, within a specified phase of a building's life cycle. Most use cases are parts of larger collaborations, where multiple use cases provide a network of collaboration links with other disciplines. This higher-level composition of use cases builds a process map [36]. Facilitating the integration and collaboration between different disciplines involved in an AEC/FM project is one of the major focuses of BIM. In fact there is a close interaction between the BIM value proposition in projects and degree of workflow integration and continuity of information flow through project life-cycle. Process maps using the Business Process Modeling Notation (BPMN) have been standardized for expressing processes of flow-oriented business operations [78]. A BPMN–based process map is used in this research to represent the project stakeholders, project phases, and information exchange between them.

Figure 56 displays the process map for the life-cycle phases of a project from a safety perspective. It shows how the automated hazard identification and prevention prototypes can be integrated in construction safety design, planning, and operation. It also explains what and how the data exchanges between the different project stakeholders can be facilitated. The contractor and the safety inspector, as the main users of the system, can implement safety planning and its integration with the construction schedule by applying the described system.

There are four major safety communication steps that take place during the construction planning and operation:

1. *Design development phase (Omniclass code: 31-20 20 00)*: The contractor needs to evaluate the design model from a safety perspective. By coordinating with safety manager, safety notes and suggestion are passed back to designer for safer design, which also helps the designer to accumulate knowledge of construction safety. For instance, for safer equipment installation and maintance, air handling unit on the roof should be designed away from the roof edge.

2. *Construction documentation phase (Omniclass code: 31-25 10 00)*: Proper safety protective equipment can be selected according to an optimized selection model. 3D safety elements can be added to the building model, attaching hazard and safety equipment information. The selection of construction elements and methods has big impact on safety. For example, instead of welding steel elements in place which may impose worker to high protential fall hazards, it is recommended to pre-weld some of the pieces in shop to shorten the installation time and hence reduce risk level on site.

3. *Construction preparation stage (Omniclass code: 31-40 20 00)*: Detailed safety planning and scheduling can help a safety manager to arrange the safety protective equipment according to needs and provide pertinent safety training to

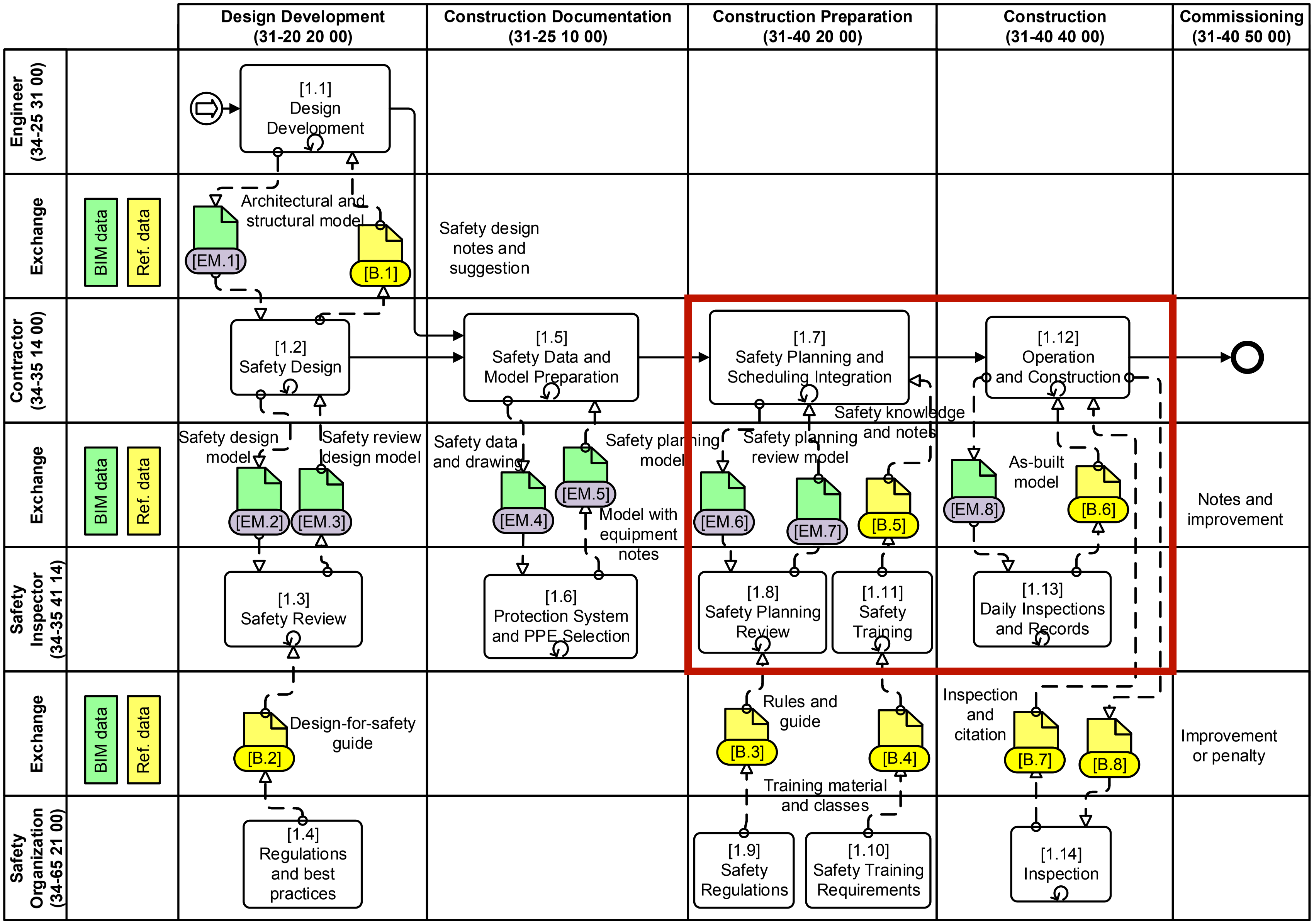


Figure 56: Process map for construction safety planning and operation.

workers. Some of the major safety tasks include site layout and logistics planning, potential hazardous zone identification and prevention, and integration of safety tasks with the construction schedule.

4. *Construction phase (Omniclass code: 31-40 40 00)*: 4D as-built model needs to be created and maintained along with the safety planning information. These are also additions that can provide safety inspectors with a helpful tool to assist in their daily inspection tasks.

Focusing on the analysis of both construction model and schedule, *Safety Planning and Scheduling Integration (Activity [1.7])* helps to identify required safety prevention equipment according to local and temporary site conditions. The schedule information of the equipment installation needs to be integrated with the construction schedule, which ensures the timely safety protection. The first application fall hazard identification and prevention is applied in this stage.

After construction begins, safety management should also operate according to the plan throughout the construction operation phase. One of the tasks of *Operation and Construction (Activity[1.12])* is to maintain as-built model and schedule, which will ensure the model and schedule to be up-to-date for safety preparation for the next day. The developed JHA and workspace tools can be applied in this stage to detect potential safety hazard and to prepare corresponding safety protective methods for the next working day.

For all of these three safety analysis prototypes, the major information needed from Tekla is geometry, object placement, and schedule. In order to understand the possibility of implementating these safety analysis on IFC-based platform, a conceptual model view using IFC schema for fall hazard identification and prevention is presented in Appendix C containing 11 major concepts. Table 13 shows a tabular report denoting which concepts could be used in which exchanges and Figure 57 shows the concept structure. Most of the concepts are defined and validated by contributors to IFC Solutions Factory-The Model View Definition site [71].

Table 13: A tabular report denoting which concepts could be used in which exchanges

Concept \ Exchange	EM.1 Architectural and structural model	EM.2 Safety design model	EM.3 Safety review design model	EM.4 Safety data and drawing	EM.5 Model with equipment notes	EM.6 Safety planning model	EM.7 Safety planning review model	EM.8 As-built model
Absolute Placement	×	×	×	×	×	×	×	×
B-rep Geometry	×	×	×			×	×	×
Quantity	×	×	×	×	×	×	×	×
Opening instance	×	×	×	×	×	×	×	×
Slab instance	×	×	×	×	×	×	×	×
Wall instance	×	×	×	×	×	×	×	×
Building Element Fills Opening	×	×	×	×	×	×	×	×
Face Connection	×	×	×			×	×	×
Assignment		×	×	×	×	×	×	×
Approval			×		×		×	×
Control		×	×	×	×	×	×	×

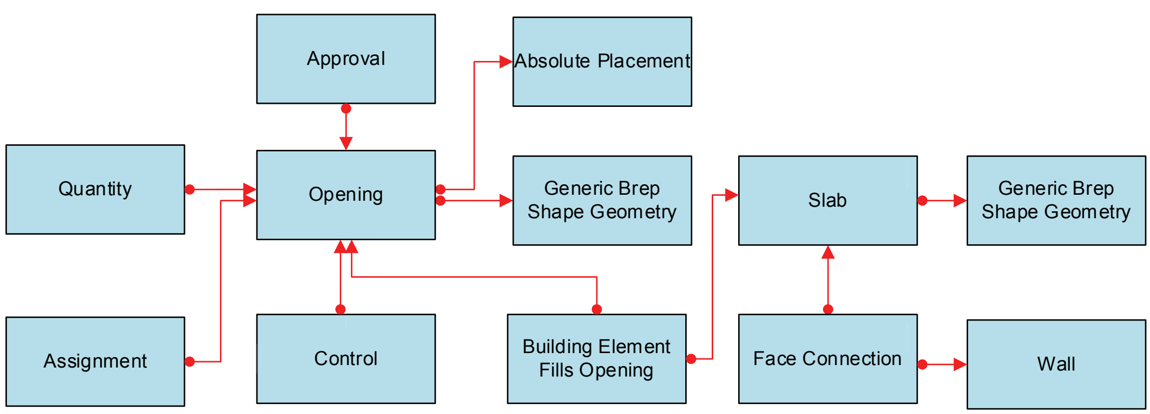


Figure 57: Concept structure

7.2 BIM Platforms Review for Supporting Safety Planning

A number of commercialized BIM platforms were examined for their capability of supporting safety planning. Several functional prerequisites are considered important to enable BIM-based safety planning. They are listed as follows:

1. Scheduling and simulation: The complex and dynamic nature of the construction industry and its on-site work patterns are widely recognized. In order to detect and prevent safety hazards during the construction process, project schedules need linkage to BIM. In addition, it is critical for the application to be able to visualize the construction progress according to the schedule to promote the safety awareness and communication.

2. Modeling: Construction safety is not only managing or controlling workers' safety behavior; it also involves the design, procurement, installation, and removal of safety and temporary equipment such as guardrails, scaffolding, and safety nets or hooks. It is essential to also design and model these temporary objects in BIM for visualization and quantification purposes. Thus, an ideal platform needs to be able to both create and modify model items.

3. Construction site layout modeling and visualization: Recognizing the importance of construction logistics and the dynamic nature of the construction site, it is important to take the construction site layout into consideration for safety. The capability of modeling and visualizing the site layout can support the detailed and accurate analysis of the site logistics which then can be used to increase productivity and enhance work site safety.

4. Model format: As mentioned earlier, the use of IFC data format allows more general checking capability of models created in various BIM authoring tools.

5. Rule-checking capability: A BIM platform equipped with its own rule engine

can provide users the opportunity to self-define or user-configured safety rules for rule-checking process.

A comparison of four existing commercially-available BIM software solutions and their potential for incorporating safety is shown in Table 14.

The strength of using Solibri Model Checker as a BIM-based tool is its capability to use IFC data exchange format, which makes the checking independent from BIM-based software used for modeling. The rule-checking functionality and user-interface also provide opportunity to incorporate safety solutions [32]. However, while automation is used to carry out the routine checking work, someone still needs to model all safety related temporary equipment and structures, which are not supported or are lacking from existing object libraries in the BIM-based modeling software. Similar issue was found with Autodesk Navisworks; the lack of modeling function makes it difficult to add safety related equipment. The dynamic nature of construction site cannot be shown in either SMC or Autodesk Revit, which makes it challenging to conduct safety review at different construction phases. Since this study focuses on building structure related hazards, site layout modeling and visualization are not in the scope of the presented work. Hence, based on the comparative analysis, Tekla Structures was chosen to function as the implementation platform that incorporates the safety requirements in this research.

Table 14: Comparison of four BIM platforms

Functionality / Application	Scheduling	Simulation	Modeling	Site layout modeling	IFC-based	Rule-checking
Autodesk Revit	–	–	√	√	–	–
Autodesk Navisworks	√	√	–	–	–	–
Solibri Model Checker (SMC)	–	–	–	–	√	√
Tekla Structures	√	√	√	–	–	–

CHAPTER VIII

CONCLUSIONS AND LIMITATIONS

This chapter summarizes the findings and concludes the thesis. Also discussed are the limitations and future extension of this research.

8.1 Conclusions

The conclusions of this research include:

- The developed ontology formalizes the construction safety knowledge and facilitates its integration with construction process.

- Hazard identification is facilitated and enhanced through linking Construction Safety Ontology with BIM.

- An empirical research approach has been developed to collect, formalize, and reuse historical activity-specific workspace information for automated activity-based workspace visualization using location tracking data.

8.2 Contributions and Impacts

The major contributions and impacts of this research include:

- The developed ontology can be used as an extensible and shareable knowledge base for construction safety management. It assists to sustain the safety knowledge within an organization such as sub-contractor to facilitate knowledge re-use. Researchers and practitioners can also further develop and customize the ontology to 1) store additional safety knowledge; 2) create extra rules to enable inferring and reasoning; 3) develop construction safety application.

- Potential fall hazards can be identified both spatially and timewise, and then corresponding prevention methods can be built into the schedule of construction project.

- Activity-based hazard identification is facilitated and enhanced through automated job hazard analysis using BIM.

- Method for rigorous data acquisition and documentation of the stochastic form of workspace activity was developed.

- Workspace conflicts can be detected in the construction planning phase which supports the identification and prevention of potential safety hazards lead by the interaction of different activities.

- The developed applications may serve as safety training material for daily safety orientation at construction site for workers so that they might understand the activity-specific safety issue and mitigation procedures to improve their safety awareness.

8.3 Limitations and Future Research

- This study heavily relies on information provided by BIM such as geometry and schedule. If the information from BIM is incomplete, incorrect, inaccurate, the safety analysis will be largely affected. Also, it cannot identify safety issues related to heavy equipment or site layout since these information currently does not exist in BIM.

- The GPS logger used in this study has comparatively low accuracy and can only work in outdoor environment. High-end and more accurate GPS logger may improve the workspace parameter accuracy. For indoor construction activities, other sensing technology such as UWB needs to be deployed instead.

- The workspace for material movement needs to be represented with various densities in the same way as worker space was considered in this study, for instance, the movement of formwork during its set up and removal. Thus, it can be used to better support 3D workspace congestion identification with an assessment of the severity of the space overlapping, which indicates the resulting potential safety risk. In addition, the user should be able to define the target potential congestion degree during the project planning based on project specific information such as site layout constraints.

- The developed applications are platform-limited. A more general approach using IFC model need to be explored. Also a detailed model view definition of construction safety needs to be studied.

- An integrated system needs to be explored in the future study to integrate rule engine for ontology within the application. Also, a computer-implemented safety language needed to be developed to enable user to define or customize their own safety rules for handling safety issues.

- The safety analysis need to be tested on real projects in the planning phase and compare the generated results with safety managers manual decisions to further understand the strengths and weakness of the tools. It can also be expanded to identify how positive outcomes of the safety analysis might be documented.

- The applicability of the safety analysis to support quantitative risk analysis needs to be explored. Safety risk factors can be computed based on the severity and likelihood of a hazard, then can be integrated into Construction Safety Ontology as properties to visualize different risk levels with color code in BIM. This can become a useful tool for safety inspector who needs to identify and resolve hazards on the construction site. Preliminary results can be found in Collins et al. [27].

APPENDIX A

CONSTRUCTION SAFETY ONTOLOGY IN OWL

The Construction Safety Ontology specification for cast-in-place column task in OWL Web Ontology Language is presented here.

```
Prefix(:=<http://www.owl-ontologies.com/Ontology1378150585.owl#>)
Prefix(owl:=<http://www.w3.org/2002/07/owl#>)
Prefix(rdf:=<http://www.w3.org/1999/02/22-rdf-syntax-ns#>)
Prefix(xml:=<http://www.w3.org/XML/1998/namespace>)
Prefix(xsd:=<http://www.w3.org/2001/XMLSchema#>)
Prefix(xsp:=<http://www.owl-ontologies.com/2005/08/07/xsp.owl#>)
Prefix(rdfs:=<http://www.w3.org/2000/01/rdf-schema#>)
Prefix(swrl:=<http://www.w3.org/2003/11/swrl#>)
Prefix(sqwrl:=<http://sqwrl.stanford.edu/ontologies/built-ins/3.4/
   sqwrl.owl#>)
Prefix(swrla:=<http://swrl.stanford.edu/ontologies/3.3/swrla.owl#>)
Prefix(swrlb:=<http://www.w3.org/2003/11/swrlb#>)
Prefix(assert:=<http://www.owl-ontologies.com/assert.owl#>)
Prefix(protege:=<http://protege.stanford.edu/plugins/owl/protege#>)

Ontology(<http://www.owl-ontologies.com/Ontology1378150585.owl>

Declaration(Class(:Activity))
SubClassOf(:Activity :Construction_Process_Model)
Declaration(Class(:Assaults_And_Violent_Acts))
SubClassOf(:Assaults_And_Violent_Acts :Potential_Hazard)
```

```
Declaration(Class(:Bodily_Reaction_And_Exertion))
SubClassOf(:Bodily_Reaction_And_Exertion :Potential_Hazard)
Declaration(Class(:Break_Forms_Loose))
SubClassOf(:Break_Forms_Loose :Job_Step)
SubClassOf(:Break_Forms_Loose ObjectSomeValuesFrom(:hasHazards :
   Unexpected_Form_Release))
SubClassOf(:Break_Forms_Loose ObjectSomeValuesFrom(:needResources :
   Concrete_Crew))
SubClassOf(:Break_Forms_Loose ObjectSomeValuesFrom(:needResources :
   Stripping_Zone))
Declaration(Class(:Building_Component))
SubClassOf(:Building_Component :Construction_Product_Model)
Declaration(Class(:Building_Component_Space))
SubClassOf(:Building_Component_Space :Work_Space)
Declaration(Class(:CIP_Column))
SubClassOf(:CIP_Column :Column)
Declaration(Class(:Column))
SubClassOf(:Column :Building_Component)
Declaration(Class(:Column_Bracing))
SubClassOf(:Column_Bracing :Concrete_Activity)
SubClassOf(:Column_Bracing DataHasValue(:needTimePercentage "18"^^xsd:
   int))
Declaration(Class(:Concrete_Activity))
SubClassOf(:Concrete_Activity :Activity)
SubClassOf(:Concrete_Activity ObjectSomeValuesFrom(:consistOf :
   Job_Step))
SubClassOf(:Concrete_Activity DataHasValue(:constructionType "
   CIP_Concrete"^^xsd:string))
Declaration(Class(:Concrete_Crew))
SubClassOf(:Concrete_Crew :Crew)
```

```
SubClassOf(:Concrete_Crew ObjectSomeValuesFrom(:occupy :
   StripColumn_WorkerSpace))
Declaration(Class(:Concrete_and_Masonry_Construction))
SubClassOf(:Concrete_and_Masonry_Construction :OSHA_1926)
SubClassOf(:Concrete_and_Masonry_Construction DataHasValue(:
   hasReference "1926.702"^^xsd:float))
Declaration(Class(:Construction_Method))
SubClassOf(:Construction_Method :Construction_Process_Model)
Declaration(Class(:Construction_Process_Model))
Declaration(Class(:Construction_Product_Model))
Declaration(Class(:Construction_Safety_Model))
Declaration(Class(:Contact_With_Objects_And_Equipment))
SubClassOf(:Contact_With_Objects_And_Equipment :Potential_Hazard)
Declaration(Class(:Crane))
SubClassOf(:Crane :Equipment)
Declaration(Class(:Crew))
SubClassOf(:Crew :Resources)
Declaration(Class(:Equipment))
SubClassOf(:Equipment :Resources)
Declaration(Class(:Equipmment_Space))
SubClassOf(:Equipmment_Space :Work_Space)
Declaration(Class(:Exposure_To_Harmful_Substances_Or_Environments))
SubClassOf(:Exposure_To_Harmful_Substances_Or_Environments :
   Potential_Hazard)
Declaration(Class(:Fall))
SubClassOf(:Fall :Potential_Hazard)
Declaration(Class(:Fall_On_Same_Level))
SubClassOf(:Fall_On_Same_Level :Fall)
DisjointClasses(:Fall_On_Same_Level :Fall_To_Lower_Level)
Declaration(Class(:Fall_To_Lower_Level))
```

```
SubClassOf(:Fall_To_Lower_Level :Fall)
DisjointClasses(:Fall_To_Lower_Level :Fall_On_Same_Level)
Declaration(Class(:Fire_And_Explosions))
SubClassOf(:Fire_And_Explosions :Potential_Hazard)
Declaration(Class(:FrameColumns_Standformsintoplace_Fall))
AnnotationAssertion(rdfs:comment :
   FrameColumns_Standformsintoplace_Fall "1. Use ladder or scaffold,
   do not use top 2 rungs of ladder/
2. Ensure area around ladder/scaffold is clear of debris and flat"^^
   xsd:string)
SubClassOf(:FrameColumns_Standformsintoplace_Fall :
   Mitigation_Recommendation)
Declaration(Class(:Frame_Column))
SubClassOf(:Frame_Column :Concrete_Activity)
SubClassOf(:Frame_Column ObjectSomeValuesFrom(:needResources :Crane))
SubClassOf(:Frame_Column DataHasValue(:needTimePercentage "19"^^xsd:
   int))
Declaration(Class(:Handling_Path))
SubClassOf(:Handling_Path :Work_Space)
Declaration(Class(:Inspection))
SubClassOf(:Inspection :Safety_Measures)
Declaration(Class(:Job_Step))
SubClassOf(:Job_Step :Construction_Process_Model)
Declaration(Class(:Material))
SubClassOf(:Material :Resources)
Declaration(Class(:Mitigation_Recommendation))
SubClassOf(:Mitigation_Recommendation :Construction_Safety_Model)
Declaration(Class(:OSHA_1926))
SubClassOf(:OSHA_1926 :Safety_Specification)
Declaration(Class(:Other_Events_Or_Exposures))
```

```
SubClassOf(:Other_Events_Or_Exposures :Potential_Hazard)
Declaration(Class(:PPE))
SubClassOf(:PPE :Safety_Measures)
Declaration(Class(:Place_Form_At_Designated_Area))
SubClassOf(:Place_Form_At_Designated_Area :Job_Step)
SubClassOf(:Place_Form_At_Designated_Area ObjectSomeValuesFrom(:
   needResources :Concrete_Crew))
Declaration(Class(:Place_Rebar_Cage))
SubClassOf(:Place_Rebar_Cage :Concrete_Activity)
SubClassOf(:Place_Rebar_Cage ObjectSomeValuesFrom(:needResources :
   Crane))
SubClassOf(:Place_Rebar_Cage DataHasValue(:needTimePercentage "17"^^
   xsd:int))
Declaration(Class(:Potential_Hazard))
SubClassOf(:Potential_Hazard :Construction_Safety_Model)
Declaration(Class(:Pour_Column))
SubClassOf(:Pour_Column :Concrete_Activity)
SubClassOf(:Pour_Column ObjectSomeValuesFrom(:needResources :Crane))
SubClassOf(:Pour_Column DataHasValue(:needTimePercentage "35"^^xsd:int
   ))
Declaration(Class(:Protective_Space))
SubClassOf(:Protective_Space :Safety_Measures)
SubClassOf(:Protective_Space :Work_Space)
Declaration(Class(:Prybar))
SubClassOf(:Prybar :Equipment)
Declaration(Class(:Remove_Pins))
SubClassOf(:Remove_Pins :Job_Step)
SubClassOf(:Remove_Pins ObjectSomeValuesFrom(:needResources :
   Concrete_Crew))
Declaration(Class(:Resources))
```

```
SubClassOf(:Resources :Construction_Process_Model)
Declaration(Class(:Retractable_Lanyard))
SubClassOf(:Retractable_Lanyard :PPE)
Declaration(Class(:Safe_Guard))
SubClassOf(:Safe_Guard :Safety_Measures)
Declaration(Class(:Safety_Definition))
SubClassOf(:Safety_Definition :Construction_Safety_Model)
Declaration(Class(:Safety_Measures))
SubClassOf(:Safety_Measures :Construction_Safety_Model)
SubClassOf(:Safety_Measures :Resources)
Declaration(Class(:Safety_Specification))
SubClassOf(:Safety_Specification :Construction_Safety_Model)
Declaration(Class(:StripColumn_WorkerSpace))
SubClassOf(:StripColumn_WorkerSpace :Worker_Space)
SubClassOf(:StripColumn_WorkerSpace DataHasValue(:
   hasWorkSpaceDepth1_100 "2.2"^^xsd:float))
SubClassOf(:StripColumn_WorkerSpace DataHasValue(:
   hasWorkSpaceDepth1_50 "1.2"^^xsd:float))
SubClassOf(:StripColumn_WorkerSpace DataHasValue(:
   hasWorkSpaceDepth1_75 "1.6"^^xsd:float))
SubClassOf(:StripColumn_WorkerSpace DataHasValue(:
   hasWorkspaceParameterNum "1"^^xsd:int))
SubClassOf(:StripColumn_WorkerSpace DataHasValue(:
   spaceReferencePosition "around"^^xsd:string))
SubClassOf(:StripColumn_WorkerSpace DataHasValue(:spaceShift1 "0.67"^^
   xsd:float))
Declaration(Class(:StripColumns_Breakformsloose_Unexpectedformrelease)
   )
```

```
AnnotationAssertion(rdfs:comment :
   StripColumns_Breakformsloose_Unexpectedformrelease "1. Barricade
   off the area to be stripped. Only authorized personnel and
   equipment are allowed in the stripping area/
2. Break one side loose prior to removing all pins/
3. Have a coworker hold the form from falling"^^xsd:string)
SubClassOf(:StripColumns_Breakformsloose_Unexpectedformrelease :
   Mitigation_Recommendation)
SubClassOf(:StripColumns_Breakformsloose_Unexpectedformrelease
   ObjectSomeValuesFrom(:require :Stripping_Zone))
SubClassOf(:StripColumns_Breakformsloose_Unexpectedformrelease
   ObjectAllValuesFrom(:IsRelatedTo ObjectIntersectionOf(:
   Break_Forms_Loose :Strip_Column :Unexpected_Form_Release)))
Declaration(Class(:Strip_Column))
SubClassOf(:Strip_Column :Concrete_Activity)
SubClassOf(:Strip_Column ObjectSomeValuesFrom(:consistOf :
   Break_Forms_Loose))
SubClassOf(:Strip_Column ObjectSomeValuesFrom(:consistOf :
   Place_Form_At_Designated_Area))
SubClassOf(:Strip_Column ObjectSomeValuesFrom(:consistOf :Remove_Pins)
   )
SubClassOf(:Strip_Column ObjectSomeValuesFrom(:needResources :Crane))
SubClassOf(:Strip_Column ObjectAllValuesFrom(:consistOf
   ObjectIntersectionOf(:Break_Forms_Loose :
   Place_Form_At_Designated_Area :Remove_Pins)))
SubClassOf(:Strip_Column DataHasValue(:needTimePercentage "11"^^xsd:
   int))
Declaration(Class(:Stripping_Zone))
SubClassOf(:Stripping_Zone :Protective_Space)
Declaration(Class(:Task))
```

```
SubClassOf(:Task :Construction_Process_Model)
SubClassOf(:Task ObjectMinCardinality(1 :produce))
Declaration(Class(:Task_CIP_Column))
SubClassOf(:Task_CIP_Column :Task)
SubClassOf(:Task_CIP_Column ObjectAllValuesFrom(:consistOf
   ObjectIntersectionOf(:Column_Bracing :Frame_Column :
   Place_Rebar_Cage :Pour_Column :Strip_Column)))
SubClassOf(:Task_CIP_Column ObjectAllValuesFrom(:produce :CIP_Column))
Declaration(Class(:Training))
SubClassOf(:Training :Safety_Measures)
Declaration(Class(:Transportation_Incidents))
SubClassOf(:Transportation_Incidents :Potential_Hazard)
Declaration(Class(:Unexpected_Form_Release))
SubClassOf(:Unexpected_Form_Release :Other_Events_Or_Exposures)
Declaration(Class(:Work_Space))
SubClassOf(:Work_Space :Resources)
Declaration(Class(:Worker_Space))
SubClassOf(:Worker_Space :Work_Space)
Declaration(ObjectProperty(:IsRelatedTo))
ObjectPropertyDomain(:IsRelatedTo ObjectUnionOf(:Work_Space :
   Mitigation_Recommendation))
ObjectPropertyRange(:IsRelatedTo ObjectUnionOf(:Activity :Job_Step :
   Potential_Hazard))
Declaration(ObjectProperty(:applyOn))
InverseObjectProperties(:needSafeGuard :applyOn)
ObjectPropertyDomain(:applyOn :Safe_Guard)
ObjectPropertyRange(:applyOn :Building_Component)
Declaration(ObjectProperty(:conflictWith))
InverseObjectProperties(:conflictWith :conflictWith)
SymmetricObjectProperty(:conflictWith)
```

```
ObjectPropertyDomain(:conflictWith :Work_Space)
ObjectPropertyRange(:conflictWith :Work_Space)
Declaration(ObjectProperty(:consistOf))
ObjectPropertyDomain(:consistOf ObjectUnionOf(:Task :Activity))
ObjectPropertyRange(:consistOf ObjectUnionOf(:Job_Step :Activity))
Declaration(ObjectProperty(:controlledBy))
ObjectPropertyDomain(:controlledBy :Potential_Hazard)
ObjectPropertyRange(:controlledBy :Mitigation_Recommendation)
Declaration(ObjectProperty(:define))
ObjectPropertyDomain(:define :Safety_Specification)
ObjectPropertyRange(:define ObjectUnionOf(:Safety_Definition :
   Protective_Space))
Declaration(ObjectProperty(:hasHazards))
ObjectPropertyDomain(:hasHazards :Job_Step)
ObjectPropertyRange(:hasHazards :Potential_Hazard)
Declaration(ObjectProperty(:isInspectedBy))
ObjectPropertyDomain(:isInspectedBy :Inspection)
Declaration(ObjectProperty(:isProducedBy))
InverseObjectProperties(:produce :isProducedBy)
ObjectPropertyDomain(:isProducedBy ObjectUnionOf(:Equipment :
   Building_Component))
ObjectPropertyRange(:isProducedBy ObjectUnionOf(:Task :Activity))
Declaration(ObjectProperty(:needResources))
ObjectPropertyDomain(:needResources ObjectUnionOf(:Job_Step :Activity)
   )
ObjectPropertyRange(:needResources :Resources)
Declaration(ObjectProperty(:needSafeGuard))
InverseObjectProperties(:needSafeGuard :applyOn)
ObjectPropertyDomain(:needSafeGuard :Building_Component)
ObjectPropertyRange(:needSafeGuard :Safe_Guard)
```

```
Declaration(ObjectProperty(:occupy))
ObjectPropertyDomain(:occupy ObjectUnionOf(:Building_Component :Crew :
   Equipment :Material))
ObjectPropertyRange(:occupy ObjectUnionOf(:Building_Component_Space :
   Equipmment_Space :Handling_Path :Worker_Space))
Declaration(ObjectProperty(:produce))
InverseObjectProperties(:produce :isProducedBy)
ObjectPropertyDomain(:produce ObjectUnionOf(:Task :Activity))
ObjectPropertyRange(:produce ObjectUnionOf(:Equipment :
   Building_Component))
Declaration(ObjectProperty(:protect))
ObjectPropertyDomain(:protect :PPE)
ObjectPropertyRange(:protect :Crew)
Declaration(ObjectProperty(:regulatedBy))
ObjectPropertyDomain(:regulatedBy :Resources)
ObjectPropertyRange(:regulatedBy :Safety_Specification)
Declaration(ObjectProperty(:require))
ObjectPropertyDomain(:require :Mitigation_Recommendation)
ObjectPropertyRange(:require :Safety_Measures)
Declaration(ObjectProperty(:train))
ObjectPropertyDomain(:train :Training)
ObjectPropertyRange(:train :Crew)
Declaration(ObjectProperty(:useMethod))
ObjectPropertyDomain(:useMethod :Activity)
ObjectPropertyRange(:useMethod :Construction_Method)
Declaration(DataProperty(:NeedTimeInterval))
DataPropertyDomain(:NeedTimeInterval :Activity)
DataPropertyRange(:NeedTimeInterval xsd:int)
Declaration(DataProperty(:constructionType))
DataPropertyDomain(:constructionType :Activity)
```

```
DataPropertyRange(:constructionType DataOneOf("CIP_Concrete"^^xsd:
   string "Masonry"^^xsd:string "Precast_Concrete"^^xsd:string "Steel
   "^^xsd:string "Temporary_Structure"^^xsd:string))
Declaration(DataProperty(:hasConflictResult))
DataPropertyRange(:hasConflictResult DataOneOf("congestion"^^xsd:
   string "design clash"^^xsd:string "no impact"^^xsd:string "safety
   hazard"^^xsd:string))
Declaration(DataProperty(:hasDistanceToEdge))
Declaration(DataProperty(:hasDistanceToLowerLevel))
DataPropertyDomain(:hasDistanceToLowerLevel ObjectUnionOf(:Job_Step :
   Building_Component))
DataPropertyRange(:hasDistanceToLowerLevel xsd:float)
Declaration(DataProperty(:hasGUID))
DataPropertyDomain(:hasGUID :Building_Component)
DataPropertyRange(:hasGUID xsd:int)
Declaration(DataProperty(:hasHeight))
FunctionalDataProperty(:hasHeight)
DataPropertyDomain(:hasHeight ObjectUnionOf(:Work_Space :
   Building_Component))
DataPropertyRange(:hasHeight xsd:float)
Declaration(DataProperty(:hasLength))
FunctionalDataProperty(:hasLength)
DataPropertyDomain(:hasLength ObjectUnionOf(:Work_Space :
   Building_Component))
DataPropertyRange(:hasLength xsd:float)
Declaration(DataProperty(:hasReference))
DataPropertyDomain(:hasReference :Safety_Specification)
DataPropertyRange(:hasReference xsd:float)
Declaration(DataProperty(:hasRiskFactor))
DataPropertyDomain(:hasRiskFactor :Job_Step)
```

```
DataPropertyRange(:hasRiskFactor xsd:float)
Declaration(DataProperty(:hasValue))
DataPropertyRange(:hasValue xsd:float)
Declaration(DataProperty(:hasWidth))
FunctionalDataProperty(:hasWidth)
DataPropertyDomain(:hasWidth ObjectUnionOf(:Work_Space :
   Building_Component))
DataPropertyRange(:hasWidth xsd:float)
Declaration(DataProperty(:hasWorkSpaceDepth1))
DataPropertyDomain(:hasWorkSpaceDepth1 ObjectUnionOf(:Activity :
   Job_Step :Work_Space))
DataPropertyRange(:hasWorkSpaceDepth1 xsd:float)
Declaration(DataProperty(:hasWorkSpaceDepth1_100))
SubDataPropertyOf(:hasWorkSpaceDepth1_100 :hasWorkSpaceDepth1)
Declaration(DataProperty(:hasWorkSpaceDepth1_50))
SubDataPropertyOf(:hasWorkSpaceDepth1_50 :hasWorkSpaceDepth1)
Declaration(DataProperty(:hasWorkSpaceDepth1_75))
SubDataPropertyOf(:hasWorkSpaceDepth1_75 :hasWorkSpaceDepth1)
Declaration(DataProperty(:hasWorkSpaceDepth2))
DataPropertyDomain(:hasWorkSpaceDepth2 ObjectUnionOf(:Activity :
   Job_Step :Work_Space))
DataPropertyRange(:hasWorkSpaceDepth2 xsd:float)
Declaration(DataProperty(:hasWorkSpaceDepth2_100))
SubDataPropertyOf(:hasWorkSpaceDepth2_100 :hasWorkSpaceDepth2)
Declaration(DataProperty(:hasWorkSpaceDepth2_50))
SubDataPropertyOf(:hasWorkSpaceDepth2_50 :hasWorkSpaceDepth2)
Declaration(DataProperty(:hasWorkSpaceDepth2_75))
SubDataPropertyOf(:hasWorkSpaceDepth2_75 :hasWorkSpaceDepth2)
Declaration(DataProperty(:hasWorkspaceParameterNum))
```

```
DataPropertyDomain(:hasWorkspaceParameterNum ObjectUnionOf(:Work_Space
    :Activity))
DataPropertyRange(:hasWorkspaceParameterNum xsd:int)
Declaration(DataProperty(:needTimePercentage))
DataPropertyDomain(:needTimePercentage ObjectUnionOf(:Job_Step :
   Activity))
DataPropertyRange(:needTimePercentage xsd:int)
Declaration(DataProperty(:spaceReferencePosition))
DataPropertyDomain(:spaceReferencePosition ObjectUnionOf(:Activity :
   Job_Step :Protective_Space :Work_Space))
DataPropertyRange(:spaceReferencePosition DataOneOf("above"^^xsd:
   string "around"^^xsd:string "below"^^xsd:string "front"^^xsd:
   string))
Declaration(DataProperty(:spaceShift1))
SubDataPropertyOf(:spaceShift1 :hasWorkSpaceDepth1)
Declaration(DataProperty(:spaceShift2))
SubDataPropertyOf(:spaceShift2 :hasWorkSpaceDepth2)
)
```

APPENDIX B

SWRL RULES

Hole(?h) $\bigwedge$ *hasWidth(?h, ?w)* $\bigwedge$ *hasLength(?h, ?l)* $\bigwedge$ *swrlb:greaterThan(?w, 2)* $\bigwedge$ *swrlb:greaterThan(?l, 2)* $\bigwedge$ *swrlb:lessThan(?w, 59)* $\rightarrow$ *needSafeGuard(?h, Cover)*

(SWRL Rule-SlabHole1)

Hole(?h) $\bigwedge$ *hasWidth(?h, ?w)* $\bigwedge$ *hasLength(?h, ?l)* $\bigwedge$ *swrlb:greaterThan(?w, 2)* $\bigwedge$ *swrlb:greaterThan(?l, 2)* $\bigwedge$ *swrlb:lessThan(?l, 59)* $\rightarrow$ *needSafeGuard(?h, Cover)*

(SWRL Rule-SlabHole2)

Hole(?h) $\bigwedge$ *hasWidth(?h,?w)* $\bigwedge$ *hasLength(?h, ?l)* $\bigwedge$ *swrlb:greaterThan(?w, 59)* $\bigwedge$ *swrlb:greaterThan(?l, 59)* $\rightarrow$ *needSafeGuard(?h, Guardrail_System)*

(SWRL Rule-SlabHole3)

CIP_Column(?cc) $\bigwedge$ *hasHeight(?cc, ?h)* $\bigwedge$ *Task_CIP_Column(?tcc)* $\bigwedge$ *produce(?tcc, ?cc)* $\bigwedge$ *consistOf(?tcc, ?pc)* $\bigwedge$ *Pour_Column(?pc)* $\bigwedge$ *consistOf(?pc, ?pgc)* $\bigwedge$ *Pouring_Columns(?pgc)* $\bigwedge$ *swrlb:greaterThan(?h, 4000.0)* $\rightarrow$ *needResources(?pgc, Platform)*

(SWRL Rule-Platform1)

Task_CIP_Slab(?tcs) $\bigwedge$ *consistOf(?tcs, ?ss)* $\bigwedge$ *Strip_Slab(?ss)* $\bigwedge$ *consistOf(?ss, ?bf)* $\bigwedge$ *Break_Forms_Loose(?bf)* $\bigwedge$ *needResources(?bf, ?sz)* $\bigwedge$ *Stripping_Zone(?sz)* $\bigwedge$ *produce(?tcs, ?cs)* $\bigwedge$ *CIP_Slab(?cs)* $\bigwedge$ *hasDistanceToLowerLevel(?cs, ?dis)* $\rightarrow$ *hasHeight(?sz, ?dis)* $\bigwedge$ *spaceReferencePosition(?sz, "below")*

(SWRL Rule-StrippingZone1)

Task_CIP_Column(?tcc) ⋀ consistOf(?tcc, ?sc) ⋀ Strip_Column(?sc) ⋀ consistOf(?sc, ?bf) ⋀ Break_Forms_Loose(?bf) ⋀ needResources(?bf, ?sz) ⋀ Stripping_Zone(?sz) ⋀ produce(?tcc, ?cs) ⋀ CIP_Column(?cc) ⋀ hasHeight(?cc, ?h) → hasWidth(?sz, ?h) ⋀ spaceReferencePosition(?sz, "around")

(SWRL Rule-StrippingZone2)

Worker_Space(?ws1) ⋀ Worker_Space(?ws2) ⋀ conflictWith(?ws1, ?ws2) → hasConflictResult(?ws1, "congestion") ⋀ hasConflictResult(?ws2, "congestion")

(SWRL Rule-SpaceConflict-WW)

Worker_Space(?ws1) ⋀ Protective_Space(?ps2) ⋀ conflictWith(?ws1, ?ps2) → hasConflictResult(?ws1, "safety hazard") ⋀ hasConflictResult(?ps2, "safety hazard")

(SWRL Rule-SpaceConflict-WP)

Worker_Space(?ws1) ⋀ Handling_Path(?ms2) ⋀ conflictWith(?ws1, ?ms2) → hasConflictResult(?ws1, "congestion") ⋀ hasConflictResult(?ms2, "congestion")

(SWRL Rule-SpaceConflict-WM)

Building_Component_Space(?bs1) ⋀ Building_Component_Space(?bs2) ⋀ conflictWith(?bs1, ?bs2) → hasConflictResult(?bs1, "design clash") ⋀ hasConflictResult(?bs2, "design clash")

(SWRL Rule-SpaceConflict-BB)

Building_Component_Space(?bs1) ⋀ Handling_Path(?ms2) ⋀ conflictWith(?bs1, ?ms2) → hasConflictResult(?bs1, "congestion") ⋀ hasConflictResult(?ms2, "congestion")

(SWRL Rule-SpaceConflict-BM)

Building_Component_Space(?bs1) ⋀ Protective_Space(?ps2) ⋀ conflictWith(?bs1, ?ps2) → hasConflictResult(?bs1, "no impact") ⋀ hasConflictResult(?ps2, "no impact")

(SWRL Rule-SpaceConflict-BP)

Worker_Space(?wc1) ⋀ Building_Component_Space(?bc2) ⋀ conflictWith(?wc1, ?bc2) → hasConflictResult(?wc1, "congestion") ⋀ hasConflictResult(?bc2, "congestion")

(SWRL Rule-SpaceConflict-WB)

Equipmment_Space(?es1) ⋀ Building_Component_Space(?bs2) ⋀ conflictWith(?es1, ?bc2) → hasConflictResult(?es1, "congestion") ⋀ hasConflictResult(?bc2, "congestion")

(SWRL Rule-SpaceConflict-EB)

Equipmment_Space(?es1) ⋀ Equipmment_Space(?es2) ⋀ conflictWith(?es1, ?es2) → hasConflictResult(?es1, "congestion") ⋀ hasConflictResult(?es2, "congestion")

(SWRL Rule-SpaceConflict-EE)

Equipmment_Space(?es1) ⋀ Handling_Path(?ms2) ⋀ conflictWith(?es1, ?ms2) → hasConflictResult(?es1, "congestion") ⋀ hasConflictResult(?ms2, "congestion")

(SWRL Rule-SpaceConflict-EM)

Equipmment_Space(?es1) ⋀ Protective_Space(?ps2) ⋀ conflictWith(?es1, ?ps2) → hasConflictResult(?es1, "no impact") ⋀ hasConflictResult(?ps2, "no impact")

(SWRL Rule-SpaceConflict-EP)

Equipmment_Space(?es1) $\bigwedge$ *Worker_Space(?wc2)* $\bigwedge$ *conflictWith(?es1, ?wc2)* $\rightarrow$ *hasConflictResult(?es1, "congestion")* $\bigwedge$ *hasConflictResult(?wc2, "congestion")*

(SWRL Rule-SpaceConflict-EW)

Handling_Path(?ms1) $\bigwedge$ *Handling_Path(?ms2)* $\bigwedge$ *conflictWith(?ms1, ?ms2)* $\rightarrow$ *hasConflictResult(?ms1, "congestion")* $\bigwedge$ *hasConflictResult(?ms2, "congestion")*

(SWRL Rule-SpaceConflict-MM)

Handling_Path(?ms1) $\bigwedge$ *Protective_Space(?ps2)* $\bigwedge$ *conflictWith(?ms1, ?ps2)* $\rightarrow$ *hasConflictResult(?ms1, "safety hazard")* $\bigwedge$ *hasConflictResult(?ps2, "safety hazard")*

(SWRL Rule-SpaceConflict-MP)

Protective_Space(?ps1) $\bigwedge$ *Protective_Space(?ps2)* $\bigwedge$ *conflictWith(?ps1, ?ps2)* $\rightarrow$ *hasConflictResult(?ps1, "no impact")* $\bigwedge$ *hasConflictResult(?ps2, "no impact")*

(SWRL Rule-SpaceConflict-PP)

APPENDIX C

CONCEPTS OF THE MODEL VIEW FOR CONSTRUCTION SAFETY PLANNING

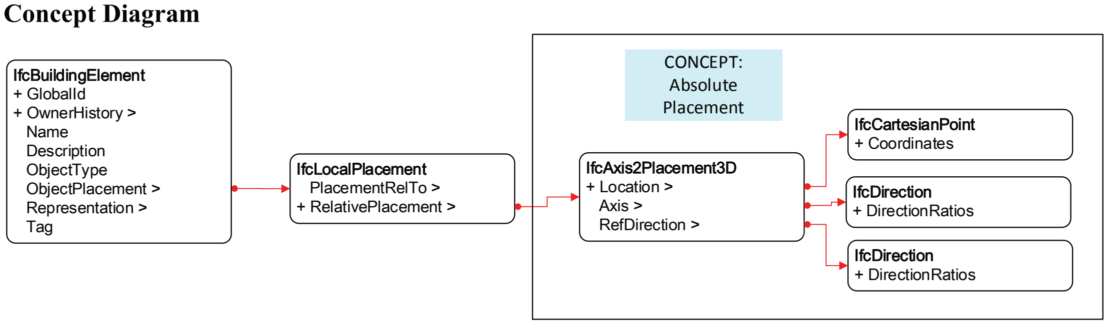
1. Absolute Placement:

IFC Release Specific Concept Description (IFC2x3) **Absolute Placement**					
Reference	PCI-064	**Version**	1.1	**Status**	Draft
Relationships	None				
History	Last reviewed November 16, 2012				
Authors	Chuck Eastman				
Editor	Precast/Prestress Concrete Institute				

Concept description

The Local Absolute Placement concept defines the local coordinate system that is referenced by all geometric representations.

Concept Diagram



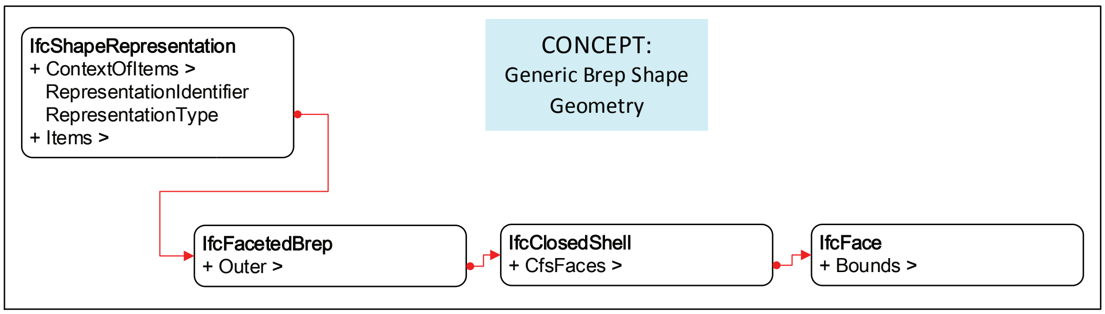
2. Generic Brep Shape Geometry:

IFC Release Specific Concept Description (IFC2x3)
Generic Brep Shape Geometry

Reference	PCI-066	**Version**	1.1	**Status**	Draft
Relationships	None				
History	Revised Nov 18, 2012				
Authors	Shiva Aram				
Editor	Precast/Prestress Concrete Institute				

Concept description
Provides Brep geometry both for building element and protective system types and instances

Concept Diagram



3. Quantity:

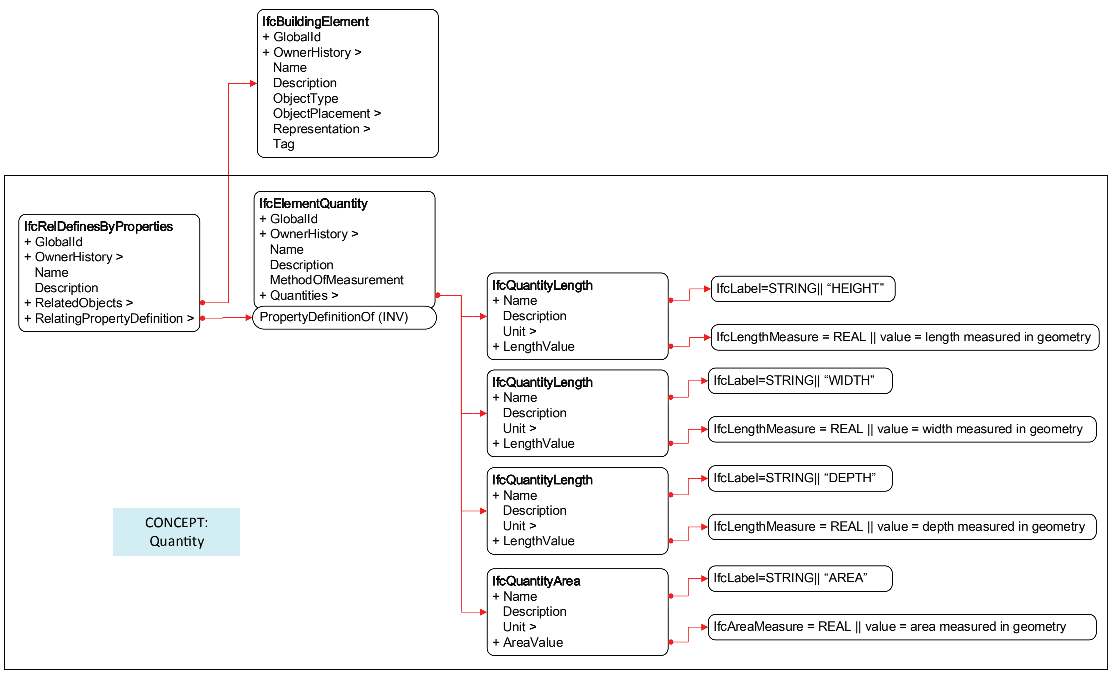
IFC Release Specific Concept Description (IFC2x3)
Quantity

Reference	SZ-001	**Version**	1.0	**Status**	Draft
Relationships	N/A				
History	Created 04/2011				
Authors	Sijie Zhang				
Editor	Sijie Zhang				

Concept description

The quantity defines the length, depth, width, and area of an IfcBuildingElement.

Concept Diagram



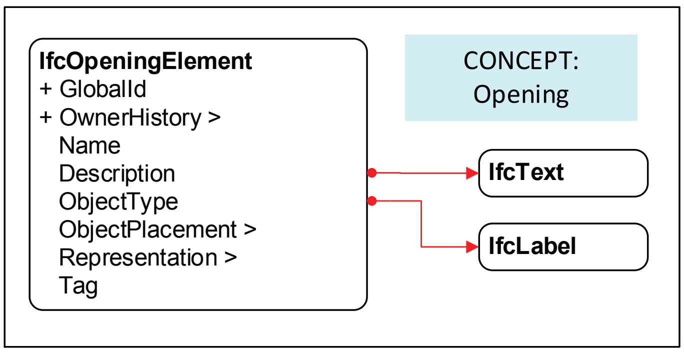
4. Opening instance:

IFC Release Specific Concept Description (IFC2x3)
Opening Instance

Reference	SZ-002	**Version**	1.0	**Status**	Draft
Relationships	N/A				
History	Created 04/2011				
Authors	Sijie Zhang				
Editor	Sijie Zhang				

Concept description
The concept defines a void in a building element. Often this void is 'filled' with other building elements such as a door, window, fixture, or equipment.

Concept Diagram



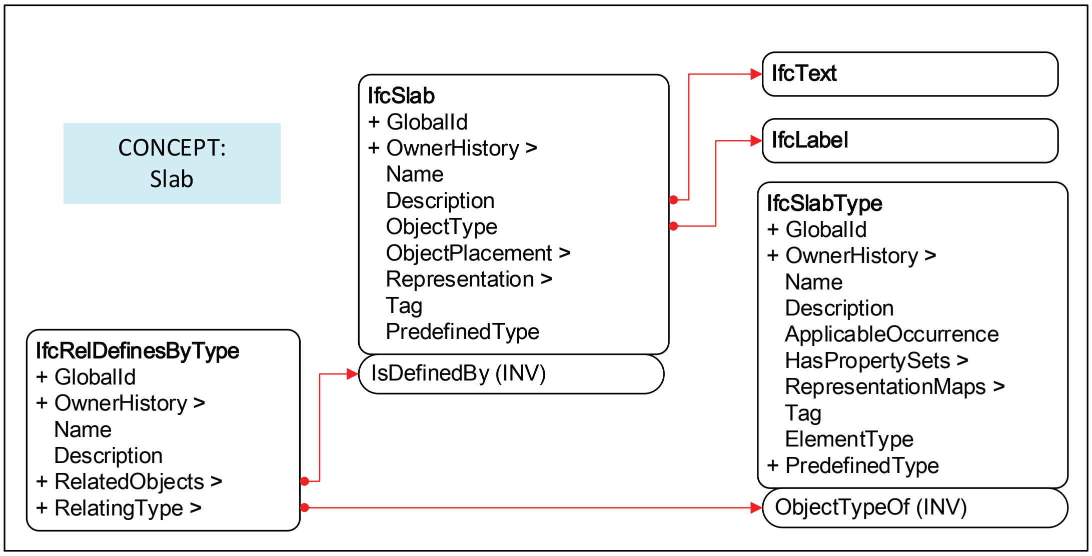
5. Slab instance:

IFC Release Specific Concept Description (IFC2x3) **Slab Instance**					
Reference	SZ-003	**Version**	1.0	**Status**	Draft
Relationships	N/A				
History	Created 04/2011				
Authors	Sijie Zhang				
Editor	Sijie Zhang				

Concept description

The concept defines the slab element and slab predefined type.

Concept Diagram



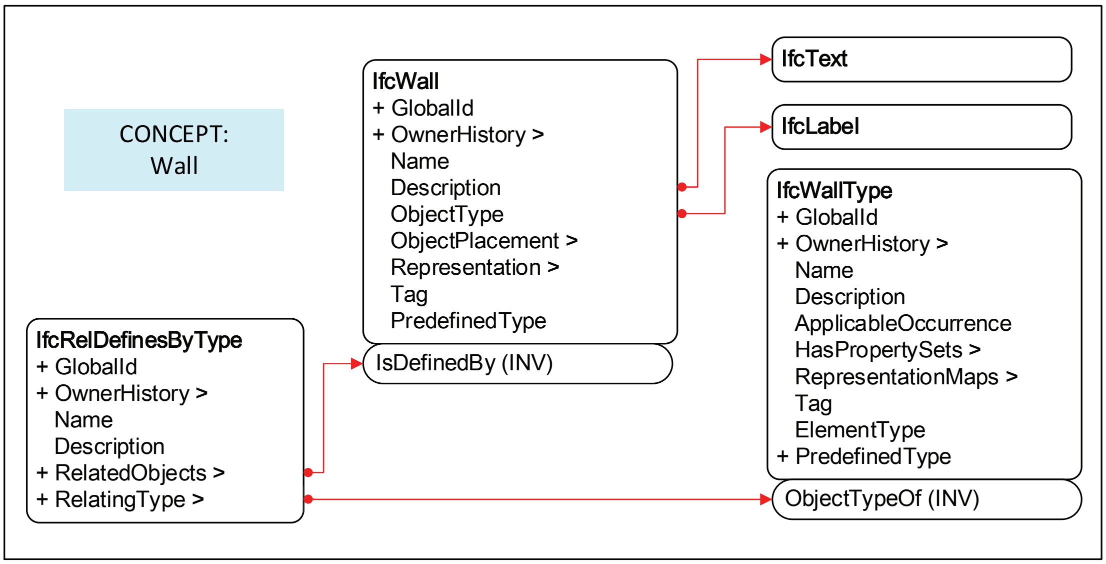
6. Wall instance:

IFC Release Specific Concept Description (IFC2x3) **Wall Instance**					
Reference	SZ-004	**Version**	1.0	**Status**	Draft
Relationships	N/A				
History	Created 04/2011				
Authors	Sijie Zhang				
Editor	Sijie Zhang				

Concept description

The concept defines the slab element and slab predefined type.

Concept Diagram



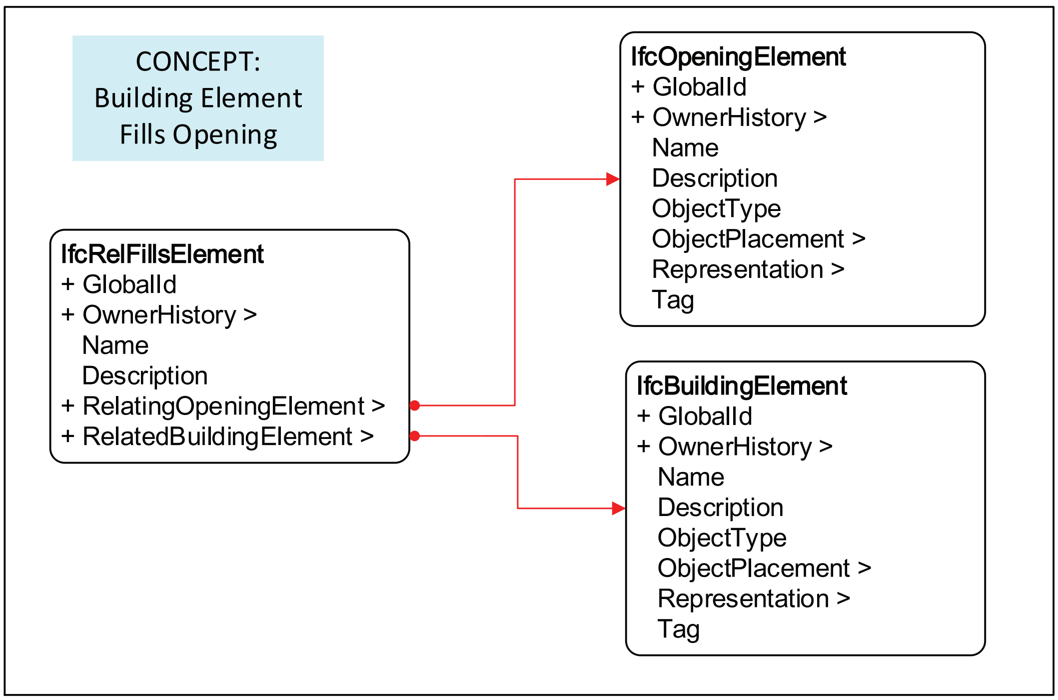
7. Building Element Fills Opening:

IFC Release Specific Concept Description (IFC2x3) **Building Element Fills Opening**					
Reference	MVC-798	**Version**	N/A	**Status**	Draft
Relationships	Generic Filling of Openings - Building Element Fills Opening				
History	This concept was previously developed by International Code Council (ICC-430)				
Authors	Richard See				
Editor	BLIS Consortium (www.blis-project.org)				

Concept description

Defines the relationship between opening and a building element that fills it.

Concept Diagram



8. Face Connection:

IFC Release Specific Concept Description (IFC2x3)

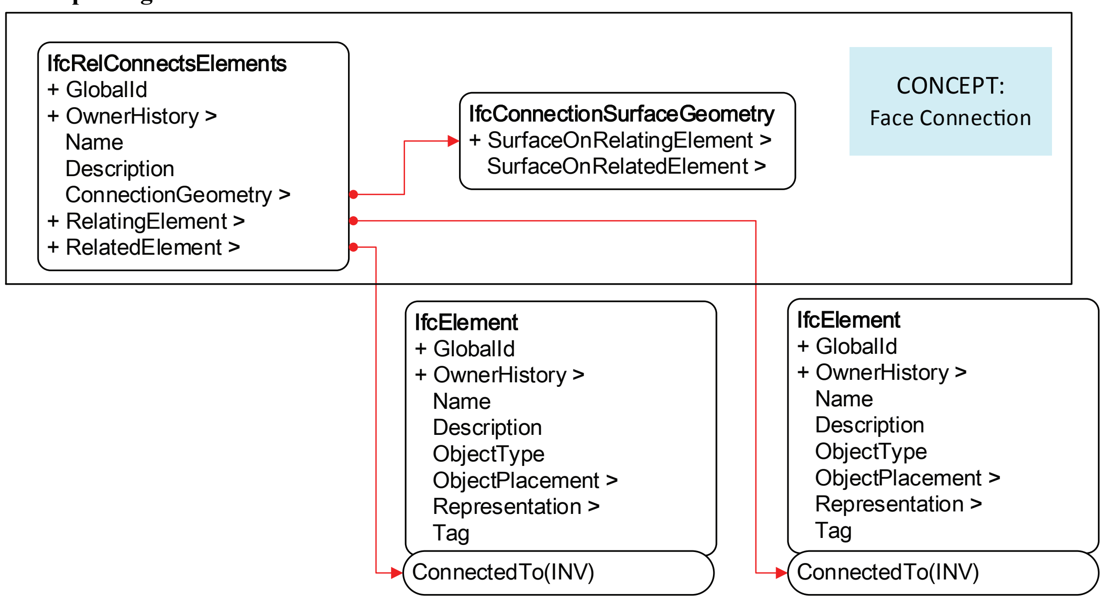
Face Connection

Reference	SZ-005	**Version**	1.0	**Status**	Draft
Relationships	None				
History	Created 04/2011				
Authors	Sijie Zhang				
Editor	Sijie Zhang				

Concept description

The concept defines the physical connection between two entities at a face on each.

Concept Diagram



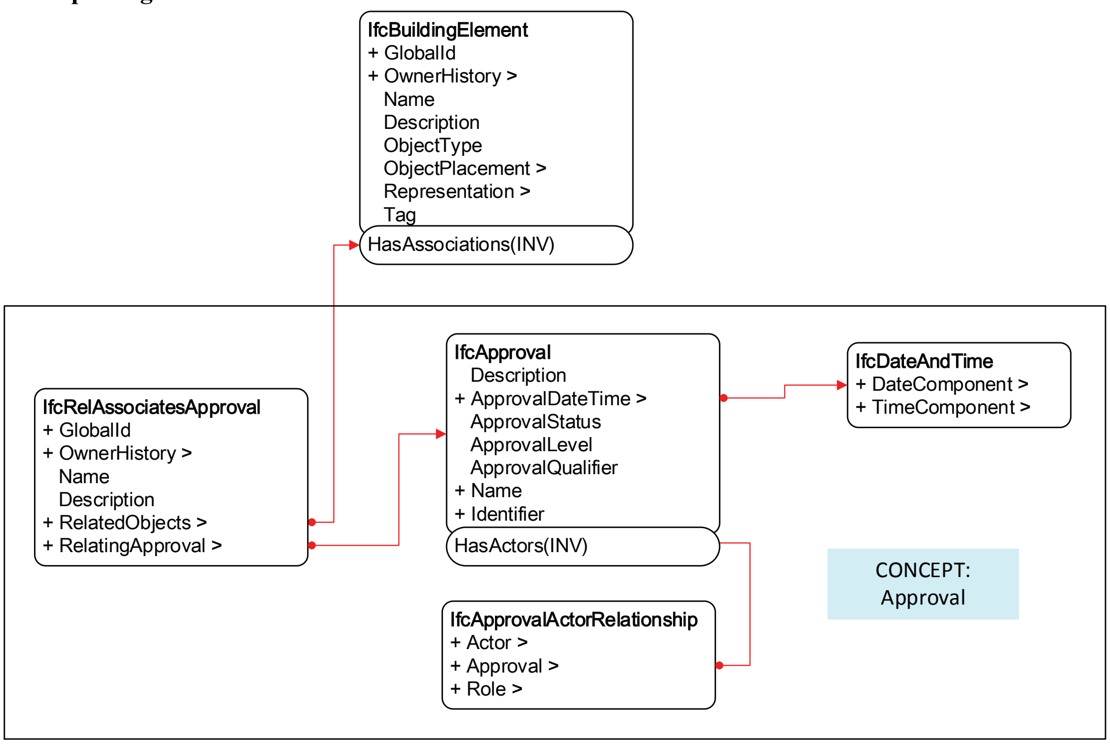
9. Approval assignment:

IFC Release Specific Concept Description (IFC2x3) **Approval**					
Reference	PCI-059	**Version**	1.1	**Status**	Draft
Relationships	None				
History	Revised Nov 18, 2012				
Authors	Shiva Aram				
Editor	Precast/Prestress Concrete Institute				

Concept description

The approval concept defines the assignment and approval of an actor (person, organization, or person + organization) to a role in the task and also the approval time.

Concept Diagram



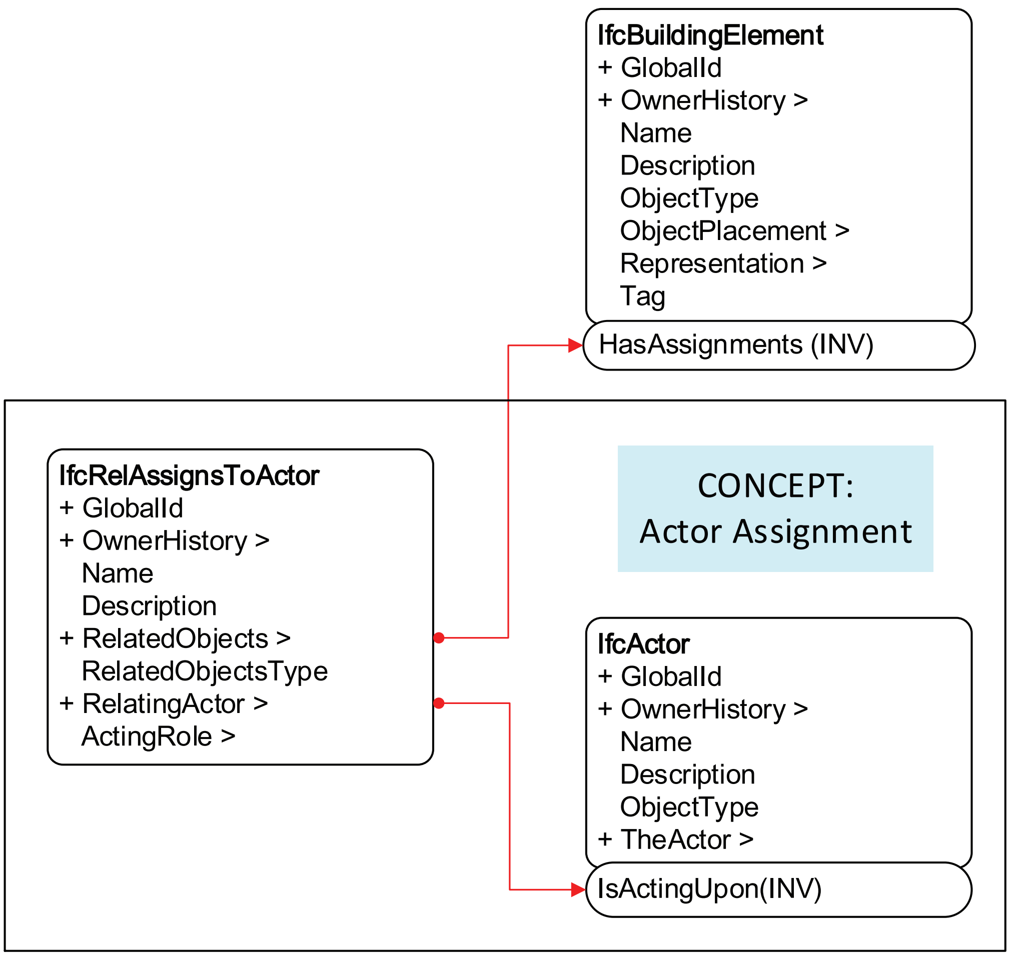
10. Actor assignment:

IFC Release Specific Concept Description (IFC2x3) **Approval**					
Reference	PCI-059	**Version**	1.1	**Status**	Draft
Relationships	None				
History	Revised Nov 18, 2012				
Authors	Shiva Aram				
Editor	Precast/Prestress Concrete Institute				

Concept description

Provides a reference to a person or an organization for building products and product types.

Concept Diagram



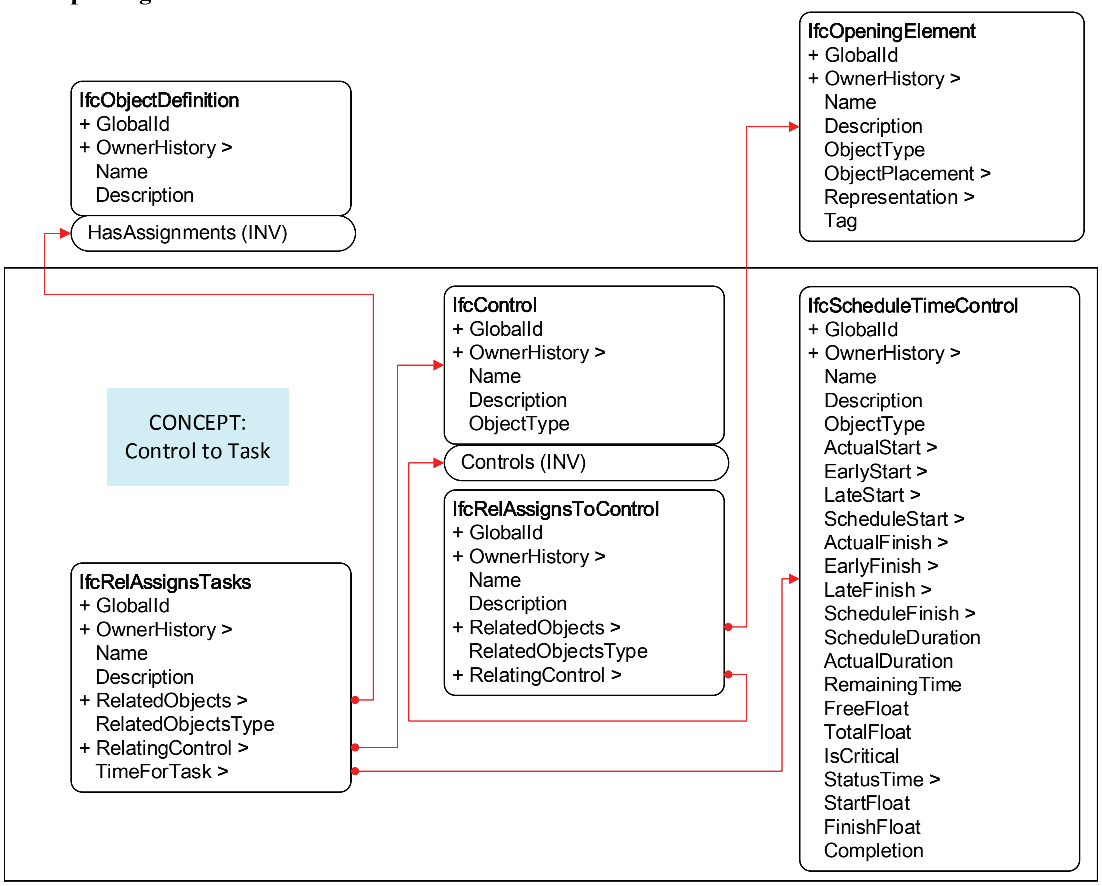
11. Control:

IFC Release Specific Concept Description (IFC2x3) **Control**					
Reference	SZ-006	**Version**	1.0	**Status**	Draft
Relationships	N/A				
History	Created 04/2011				
Authors	Sijie Zhang				
Editor	Sijie Zhang				

Concept description

The control concept defines the prevention system

Concept Diagram



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